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Prospects for Soil Regeneration and Its Impact on Environmental Protection

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Editors

Prospects for Soil Regeneration and Its Impact on Environmental Protection

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Foreword

Soil is a complex system of inorganic and organic materials, living organisms, water, and air. It is home to more than one trillion species of microorganisms. Soil plays an important role in the global carbon cycle. Because plants absorb carbon from the atmosphere, convert it to plant tissue, and return it to the soil as plant residue, soils globally act as the world's largest sink of active carbon. Soil has role to play in food production and safety. Soil contamination undermined by modern agricultural practices depletes soil carbon stocks. Anthropogenic greenhouse gas emissions have been raising recorded temperatures since the industrial revolution. Greenhouse gas emissions from agriculture, forestry, and fisheries have almost doubled in the last 50 years and will increase by 30% in the year 2050 given the current trend. With atmospheric carbon dioxide reaching 400 parts per million in 2016, soils can be an ally in bringing the CO_2 level down to a sustainable level if protected for regeneration. Soil protection and regeneration is a technique that involves the conservative rehabilitation of soil ecosystem and farmland. This technique focuses on top soil regeneration, improving the water cycle, supporting biosequestration, enhancing ecosystem services, increasing biodiversity, strengthening the vitality and health of farm soil, increasing resilience to climate change and landscape. Environmental protection not only improves soil health, productivity, and resilience to weather extremes, raising farm yields and income while strengthening regional food security in the face of a changing climate, but can also form part of a region's broader climate strategy.

This book is timely, as more studies and reviews need to be reported on regenerating global polluted soil and the impacts on the environment, the benefit of both biotic and abiotic structure thereby creating more awareness of environmental protection and sustainability. Thus, this volume presents a vista to research on regeneration of lost resources in the soil and its impacts on the environment. The book *Prospects for soil regeneration and its impact on environmental protection* is a good collection of independent chapters which presents full insights in the study of soil regeneration after contamination and the effect on the general environments. In an expansive form, this book focuses on the legislation and programs supporting environmental protection/conservation for sustainable agriculture, landscapes, and climatic change perspective. General and current information on soil formation, depletion and/or regeneration, and women empowerment in environmental protection were critically reviewed in this volume. Also, the role of soil microbial community in soil rejuvenation for food security was also fully discussed among others. I therefore have no doubt that the areas covered in this book have provided adequate information on soil regeneration and its impact on environmental protection by filling the expected scientific knowledge gaps in these areas.

October 2023

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Preface

This book titled *Prospects for Soil Regeneration and its Impact on Environmental Protection* has been designed to give current scientific information on the soil regeneration prospects and how it impacted the environmental protection. The concept of the environment has been defined as the sum total of all surroundings of a living organism, including natural forces and other living things, which provide conditions for development and growth as well as of danger and damage. Soil is constantly polluted through numerous sources by both organic and inorganic constituents. This deteriorating planetary condition, along with a deepening scientific understanding of and support for regenerative agriculture, is the ecological context for this book. Soils not only have a key role in fulfilling specific nutritional needs of plants. Soil also performs many ecosystem services, including carbon sequestration; water purification and soil contaminant reduction; climate regulation; nutrient cycling; providing a habitat for organisms; flood regulation; producing genetic resources and pharmaceuticals; and providing food, fuel, and fiber. Most of the developing countries have long time since established laws and formal governmental structures to address their serious environmental problems, but few of them have been successful in alleviating those problems. The objective of this book was designed to stimulate discussion about the prospects for soil regeneration and its impact on environmental protection.

This book placed heavy emphasis on the state of the environment and revitalization of soil policies. It focuses on conservative agriculture, animals, and water for sustainable environment. Nevertheless, administrative aspect of environmental laws has been a major issue of environmental conservation and protection policies, it is now recognized that administration in many countries of the world is a neglected factor and it is tremendously inadequate.

The analysis of the book will help readers to understand and draw attention to the issues such as the concerns of soil pollution and regeneration. Be that as it may, three sections were designed to accommodate 18 chapters. *Environmental conservation policies*, *Soil and soil issues, and Soil regeneration and influencing factors.* Part

1 consists of four chapters. The first chapter "Legislation and Programs Supporting Environmental Protection" reviewed the legislation and programs supporting environmental protection. Chapters "Environmental Conservation for Sustainable Agriculture"–"Impact of Emerging Contaminant on Farmland Soil" revealed the environmental conservation for sustainable agriculture, environmental conservation for sustainable rural and urban development, and impacts of emerging contaminant on farmland soils, respectively. The second section of the book comprises five chapters and designed to tackle different issues facing soil ranging from soil formation, soil health and soil biodiversity, topsoil regeneration and biosequestration, soil erosion, mineral depletion and regeneration, recycling resources of soil and agroecosystem, and **n**atural occurrence of soil dilapidation were broadly discussed. The third section of this book with nine chapters laid emphasis on the soil regeneration and influencing factors. Issues on regenerative agriculture for food security couple with soil regeneration and microbial community activities on terrestrial food chain, This section was designed also to review the impact of regenerative agriculture on soil erosion, advantages and disadvantages of soil regeneration, microorganisms: role in soil ecosystem restoration, rural and urban development: pathways to environmental conservation and sustainability, soil microbiome in nutrient conservation for plant growth, women empowerment in environmental conservation, and the future direction of environmental conservation and soil regeneration were examined.

The chapters were contributed by 70 academicians/scientists/researchers from 12 different countries (China, India, Nigeria, Canada, Ghana, South Africa, USA, UK, Hong Kong, Sweden, Australia, and Rwanda) across the world.

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Ogbomoso, Nigeria — Babafemi Raphael Babaniyi, Ph.D. (in view)
Minna, Nigeria — Adejoke Blessing Aransiola, Dipl.-Ing.
Portoviejo, Ecuador — Naga Raju Maddela, Ph.D.

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About the Editors

Sesan Abiodun Aransiola obtained his first degree (B.Tech.) and Master Degree (M.Tech.) from the Federal University of Technology, Minna, Niger State, Nigeria at the Department of Microbiology in 2009 and Environmental Microbiology in 2014, respectively. He had a Ph.D. Degree in Environmental Microbiology in the same institution. To his credit, there are over 70 publications including book chapters, research and review articles of international repute. He has co-edited scientific books of global interest. Also, he is a Lecturer at the Department of Microbiology, University of Abuja and also has worked as an Assistant Chief Scientific Officer at Bioresources Development Centre, National Biotechnology Development Agency, Nigeria. His area of interest is Environmental Microbiology with research area in phytoremediation, vermicomposting, biosorption and bioremediation of soil contaminated environment. He is a member of Nigerian Society for Microbiology and American Society for Microbiology among others.

Babafemi Raphael Babaniyi is a graduate of Industrial Chemistry (B.Sc.) at Caritas University Amorji-Nike, Emene, Enugu State, Nigeria in 2008. Later had his Master Degree (M.Tech.) in Environmental Chemistry at Federal University of Technology, Akure, Ondo State, Nigeria in 2021. Currently, he is a Ph.D. (in view) candidate in the Department of Chemistry (Environmental Chemistry) Federal University of Technology, Akure, Ondo State, Nigeria. He had over 25 publications including book chapters and articles of international repute. Additionally, he is an Assistant Chief Scientific Officer at Bioresources Development Centre, National Biotechnology Development Agency, Nigeria. His area of interest is Environmental Chemistry with research area in environmental chemistry, green chemistry, phytoremediation, chemical biology, environmental science, bioremediation of soil contaminated environment, plant protection and animal health, environmental impact assessment, and biodegradable plastics.

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Naga Raju Maddela received his M.Sc. (1996–1998) and Ph.D. (2012) in Microbiology from Sri Krishnadevaraya University, Anantapuramu, India. During his doctoral program in the area of Environmental Microbiology, he investigated the effects of industrial effluents/insecticides on soil microorganisms and their biological activities and he is working as Faculty in Microbiology since 1998, teaching undergraduate and postgraduate students. He worked as Prometeo Investigator (fellowship received from SENESCYT) at Universidad Estatal Amazónica, Ecuador during 2013–15, received "Postdoctoral Fellowship" (2016–2018) from Sun Yat-sen University, China. He also received external funding from "China Postdoctoral Science Foundation" in 2017 and internal funding from "Universidad Técnica de Manabí" in 2020. He participated in national/international conferences, and presented research data in China, Cuba, Ecuador, India, and Singapore. Currently, he is working as a Full Professor at the Facultad de Ciencias de la Salud, Universidad Técnica de Manabí, Portoviejo, Ecuador. He has been actively publishing scientific articles, books (authored and edited), and chapters since 2007. As of now, he published 70 articles, 12 books, and 40 book chapters.

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Environmental Conservation Policies

Legislation and Programs Supporting Envronmental Protection

Gabriel Gbenga Babaniyi, Ulelu Jessica Akor, and Joshua Ibukun Adebomi

Abstract The Environmental Protection Program employs a methodical strategy for overseeing perilous substances and ecological matters that endeavors to heighten community awareness regarding environmental impacts. This review provides an in-depth examination of the laws and initiatives established to uphold environmental conservation. Moreover, it offers a methodical assessment of the hurdles associated with applying the Environmental Protection and Management Act, all in pursuit of achieving sustainable development. This review delineates the relevant legislation, fundamental principles, and established methodologies pertaining to the subject matter at hand. The Environmental Protection Program endeavors to enhance public cognizance of the repercussions of environmental alterations through the systematic management of dangerous substances and environmental predicaments. The environmental policy of Nigeria incorporates a set of legal and regulatory frameworks, standards, protocols, and governance mechanisms that aim to govern and mitigate activities that may potentially result in adverse effects on the country's ecosystem. The establishment of environmental legislation represents a deliberate effort to confront a range of ecological pollutants, which encompasses, but is not constrained to, noxious chemicals and audible disturbances. The present article posits that the integration of environmental sustainability education within the academic curricula of primary, secondary and tertiary schools is of paramount importance. This assertion stems from the pressing need to address the increasing threat of environmental degradation, which highlights the importance of promoting greater awareness and understanding of ecological systems and their impacts on human well-being. Furthermore, this article emphasizes the need to accord greater gravity to environmental pollution

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awareness campaigns, in recognition of their underlying significance for ensuring a sustainable future.

Keywords Environmental pollution · Environmental degradation · Environmental sustainability · Environmental protection

1 Introduction

The Environmental Protection Program (EPP) constitutes a distinctive element within the Environmental Health and Safety Department, undertaking a comprehensive assessment, surveillance, and regulation of environmental discharges encompassing air, water, hazardous waste, and assets. The primary objective is to ensure that releases into the environment adhere to safety standards, compliance requirements, and cost-effectiveness [1]. Employing a systematic approach, the Environmental Protection Program manages hazardous materials and environmental affairs, actively promoting awareness of environmental impacts within the community. Contrastingly, environmental action programs furnish a sweeping policy framework delineating the principal medium- and long-range objectives of environmental policy. This includes a foundational strategy specifying concrete measures as needed [2].

1.1 Environmental Protection and Management Act

This law is designed to make sure that decisions about the environment involve collaboration among relevant authorities, non-governmental organizations, and other stakeholders. It covers measures to prevent and address various types of environmental damage or pollution. Moreover, the law aims to enhance the understanding and value of the environment among all individuals. It regulates social relationships related to the collection and access to environmental information, outlining the rights and obligations of the State, municipalities, legal entities, and individuals concerning environmental protection. By emphasizing principles such as public participation, transparency in decision-making, awareness of environmental conditions, and access to justice in environmental matters, this legal framework lays the groundwork for safeguarding the environment [3].

1.2 Program for the Prevention of Environmental Risks

This is a part of Regulation No. 9, aiming to implement measures that neutralize or limit environmental risks faced by workers in their workplaces. Every employer and institution that hires individuals as employees, according to this Regulation, must develop and implement the Environmental Risk Prevention Program (PPRA). The PPRA's purpose is to safeguard the health and well-being of employees by proactively identifying, assessing, and controlling existing or potential environmental risks in the workplace. In simpler terms, employers and institutions must create PPRA, which includes assessments of the work environment, environmental data, and strategies to control individual and collective risk factors. This document should be accessible to workers and regulatory agencies involved in occupational health and safety [2–5].

1.3 Environmental Risks

Fernanda Coelho [4] noted that environmental risks are taken into account in accordance with the PPRA.

Physical Agents: These refer to different forms of energy that workers might encounter, including noise, vibrations, extreme pressures, high temperatures, ionizing radiation, non-ionizing radiation, infrasound, and ultrasound. In simpler terms, physical agents are various kinds of energy in the workplace that can affect employees [3].

Chemical Agents: Substances or items classified as chemicals are ones that can enter the body by respiratory inhalation, either as dust, fumes, mists, gases, or vapours. On the other hand, they may also come into touch with the skin or be consumed, going into the body through various channels according on the circumstances surrounding the exposure.

Biological Agents: These encompass bacteria, fungi, bacilli, parasites, protozoa, and viruses, among other things. In simpler terms, biological agents are different types of microorganisms and parasites that can be present in the work environment [3].

2 Environmental Legislation

There are some key pieces of environmental legislation in Nigeria as highlighted by Sodipo et al. [6] which are as follow:

- Environmental governance in Nigeria revolves around key legislations, prominently the National Environmental Standards Regulation and Enforcement Agency (Establishment) Act of 2007 (NESREAA) and the accompanying 33 regulations issued by the Environment Minister, as per Section 34 of the Act. This law, aligned with Section 20 of Nigeria's 1999 Constitution, replaced the Federal Environmental Protection Act of 1988. NESREA holds the pivotal role in enforcing all environmental laws, rules, regulations, policies, and standards. It serves as the primary government body dedicated to overseeing environmental protection in Nigeria, ensuring adherence to environmental agreements, treaties, and conventions ratified by the country [7].

- The Environmental Impact Assessment Act (Cap. E12 LFN 2004) is another significant legal framework. This statute delineates the fundamental guidelines, processes, and techniques for conducting environmental impact assessments across various industries [8].
- Furthermore, the legislation titled "Act Concerning Harmful Waste (Special Criminal Provisions, etc.) (Cap. H1 LFN 2004)" explicitly prohibits the transportation, disposal, and dumping of hazardous materials on both land and in waterways. In simpler terms, this law aims to prevent the improper handling and disposal of harmful waste materials, emphasizing the criminality associated with such actions [3].
- Additionally, to streamline the oversight of wildlife management, conservation, and protection of endangered species, the "Act for the Regulation of International Trade and Traffic in Endangered Species (Cap. E9 LFN 2004)" was established in alignment with various international treaties.
- In 2006, a law was enacted to set up the National Oil Spill, Detection, and Response Agency (NOSDRA), aiming to create a vital structure for coordinating and implementing Nigeria's National Oil Spill Contingency Plan. The main goal of this legislation is to ensure a safe, timely, effective, and appropriate response to substantial or catastrophic incidents of oil pollution. In simpler terms, this law is designed to manage and address the consequences of significant oil spills, emphasizing the need for a well-coordinated and efficient plan to respond to such incidents [9].
- Furthermore, the National Park Services Act (Cap. N65 LFN 2004) has the purpose of protecting the ecosystem, encompassing vegetation, within national parks [9].
- The 2007 Nigerian Mining and Minerals Act. This repealed the Minerals and Mining Act No. 34 of 1999 and reenacted the Nigerian Minerals and Mining Act 2007 to govern, among other things, the exploration of solid minerals [10].
- The Water Resources Act (Cap. W2 LFN 2004) aims to promote the optimal use, conservation, and exploitation of water resources [11].
- The Hydrocarbon Oil Refineries Act is a law that oversees and grants licenses for refining operations.
- The Associated Gas Re-Injection Act is focused on the activities of oil and gas companies participating in gas flaring. It forbids any oil and gas company from engaging in gas flaring in Nigeria without a valid permit and outlines the consequences for breaching this prohibition.
- The use of radioactive materials and devices that release ionizing radiation is governed by the Nuclear Safety and Radiation Protection Act. In example, it makes it possible to create laws that safeguard the environment from ionizing radiation's damaging impacts.
- The Oil in Navigable Waters Act governs the discharge of oil from ships, prohibiting the release of oil from ships into national or local seas or shorelines.

2.1 Regulatory Bodies

In Nigeria, there are several national regulatory agencies:

1. NESREA, which stands for the National Environmental Standards and Regulations Enforcement Agency.
2. The organization responsible for detecting and responding to oil spills.
3. Federal Environment Ministry.
4. The DPR, or Directorate of Petroleum Resources.
5. Regulatory Agency for Nuclear Energy in Nigeria.
6. Federal Water Resources Ministry.
7. Agency for the Detection and Response to Oil Spills (NOSDRA).
8. National Biosafety Management Organization.
9. Office of Climate Change.
10. Nigeria's Energy Commission 10.
11. Coastal zone management, flooding, and erosion.
12. Planning, Research, and Statistics Department.
13. Agency for Combating Desertification

Each of Nigeria's 36 states has its own agencies for environmental protection. For instance, Lagos State Environmental Protection Agency (LASEPA) is a representative example. LASEPA gives officers the power to search, seize illegal items, and detain violators. Violations under the LASEPA law include actions like improperly disposing of untreated human waste into canyons, public drains, or any other land area. It's strictly forbidden to release oil, grease, or used oil into public drains, watercourses, gorges, or roadsides [12].

Similarly, the Akwa Ibom State Environmental Protection and Waste Management Act (EPWMA) outlines similar regulations, authorizing inspectors to inspect sites and collect garbage samples. Offenders under this Act are taken to the Environmental Sanitation Court, which has authority over individuals and organizations, as specified in the EPWMA. Offenses include the burial or disposal of expired medications or chemicals without the proper permit. Consequently, using pesticides, herbicides, insecticides, or other chemicals to eliminate fish or aquatic life in rivers, lakes, or streams is considered illegal.

Under the Environmental Impact Assessment Act (CAP E12 LFN 2004), organizations are required to conduct an environmental impact assessment, considering the potential environmental effects of any public or private projects [8]. This requirement becomes particularly important when a proposed project has the potential to significantly harm the environment due to its size, nature, or location. Violators of the EIA Act face potential imprisonment of up to five years or fines upon conviction, with corporations also subject to financial penalties.

2.2 Contamination of Land

Concerns regarding polluted land are under the authority of the National Environmental Standards and Regulation Enforcement Agency (NESREA) and the Harmful Waste (Special Criminal Provisions, etc.) Act. Operators are required to handle and fix polluted sites, following the directions in the Environmental Guideline and Standards for the Petroleum Industry in Nigeria (EGASPIN). In situations where legal breaches are suspected, the power to perform searches is activated. Under NESREAA, authorized individuals have the right to enter and search any location where an offense is suspected, like land, buildings, vehicles, tents, vessels, floating crafts, inland waters, or any other structures, if there is a reasonable suspicion of a crime.

As per the Harmful Waste (Special Criminal Provisions, etc.) Act, it is against the law for anyone to move, deposit, or dump dangerous waste on land without the necessary permission. Similarly, following Section 27 of the National Environmental Standard and Regulation Enforcement Agency Act (NESREAA), releasing harmful substances in quantities that are considered damaging to the land without permission is a punishable offense, carrying a potential penalty of up to five years in prison or a fine of NGD1 million. In cases where a corporation commits an offense, both the corporation and individuals in control or responsible for the business at the time of the offense are deemed culpable. Offenders may incur an additional fine of NGD $50,000 for each day the offense persists. Beyond fines, those responsible are accountable for removal costs, including expenses undertaken by government entities for the restoration or replacement of natural resources.

The "polluter pays" principle is in effect, requiring the party accountable for pollution to cover removal costs. This includes expenses incurred by government bodies or the National Environmental Standards and Regulation Enforcement Agency (NESREA) for the restoration or replacement of natural resources. It also encompasses costs by third parties for reparation, restoration, restitution, or compensation. Ensuring the restoration of soil and groundwater to safe levels is crucial for the polluter. The owner or occupier of a property must investigate and address contamination unless they can demonstrate that the discharge resulted solely from a natural disaster, act of war, or sabotage.

The Environmental Guidelines and Standards for the Petroleum Industry in Nigeria (EGASPIN) establish individual responsibility for a spiller regarding their actions. In cases involving multiple spillers, the responsibility is both collective and individual. If a previous owner or occupier contributed, wholly or partially, to the pollution on a property, and the agreement between the parties did not completely transfer the liabilities to the current owner/occupier, an individual has the right to take legal action to seek compensation from that owner. The terms of a polluter's contract determine whether they can transfer the obligation for contaminated land to a buyer. Nigerian law adheres to the principle of "buyer beware," presuming that potential buyers have diligently examined the situation before finalizing an asset purchase [12].

3 Environmental Protection Support Program

The Environmental Protection Program (EPP) operates as a distinctive element in the Environmental Health & Safety Department. It conducts comprehensive evaluations, monitoring, and control of environmental releases, encompassing air, water, hazardous waste, and assets. The program is dedicated to ensuring that environmental releases are not only safe and compliant but also economically viable [13]. By systematically managing hazardous substances and environmental concerns, the Environmental Protection Program strives to enhance public awareness regarding the impacts of environmental changes.

Different environmental management initiatives have been implemented to guarantee adherence to municipal, state, and federal environmental standards. Each program has corresponding written plans, procedures, or instructions outlined in the documentation to meet specific requirements. Environmental Programs, as described in the Instructions to Bidders [14], pertain to the Owner's environmental plans, programs, procedures, and requirements documented in the Owner's handbook. Notable examples include the Owner's Asbestos Control Program, Mold Program, and a program for regulating and handling designated substances.

Raimi [13] emphasizes that recognizing the significance and benefits of environmental protection for sustainable development has brought environmental concerns to the forefront at national, sub-regional, regional, and international levels. Despite this awareness, the world continues on unsustainable paths, leading to adverse effects on the environment. Industrialization, technological advancements, and economic growth have notably improved human quality of life. However, various environmental issues, both natural and human-induced, now pose threats to human health and ecosystems [12].

To enforce environmental protection controls and preserve the environment, numerous national and international initiatives have been initiated by regulatory bodies and the business sector. In Nigeria, environmental pollution is a significant concern [15]. The Niger Delta faces severe environmental degradation due to oil industry activities, while cities like Lagos grapple with massive waste heaps blocking many of the state's natural inland waterways [16]. Conducting Environmental Impact Assessments (EIAs) as required by law whenever an individual or company engages in activities potentially harmful to the environment is crucial [17]. These reports must clearly outline the environmental risks associated with the proposed activity and detail the precautions to be taken to mitigate those risks. According to Onapajo and Ozden [16], apart from Environmental Impact Assessment EIA reports that must be submitted for certain activities that are considered to be environmentally harmful, there are permits that are applicable to specific economic sectors, such as:

- Authorizations from the Nigerian Nuclear Regulatory Authority are required for those involved in operations that produce radioactive waste.
- FEPA permits are required for the treatment, evacuation, and discharge of dangerous hazardous waste into natural waterways including lakes and rivers.

3.1 Laws, Benchmarks, Controls, and Organizations Relating to the Environment in Nigeria

The environmental policy of Nigeria encompasses the statutory frameworks, benchmarks, protocols, and governance measures implemented to regulate practices that pose a risk of causing negative impacts on the natural surroundings of the nation. Environmental legislation has been established with the objective of addressing diverse environmental pollutants, including but not limited to toxic chemicals and noise. These regulations additionally seek to oversee particular activities like mining and power generation while concurrently furnishing overarching guidelines for the protection of essential natural resources such as air, land, and water [18].

Environmental laws in Nigeria encompass a varied array of legal instruments, including comprehensive framework environmental legislation, sector-specific laws, and incidental legislation. The conceptualization of framework environmental legislation involves a comprehensive law that constitutes a system geared towards the effective management of the environment [19]. Numerous legislative measures have been instituted in Nigeria to address the management of harmful waste. The legal structure in Nigeria concerning the disposal and control of hazardous waste includes acts such as the Harmful Wastes (Special Criminal Provisions) Act of 1988 (Cap 165 LFN 1990), the Federal Environmental Protection Agency (FEPA) Act of 1988 (Cap 131 LFN 1990), the Environmental Impact Assessment (EIA) Act of 1992, and the Nigerian Urban and Regional Planning Act [20].

Regarding specific aspects of the environment and human activities, legislation specific to sectors covers a range of laws like the Mineral Act of 1956, the Oil Pipeline Act of 1958, the Oil in Navigable Waters Act of 1968, the Petroleum Act of 1969, and the Factories Act of 1987. Laws not primarily designed for environmental issues but having environmental consequences fall under incidental legislation. Importantly, the Water Works Act of 1915, the Criminal Code of 1916 (Cap 77 LFN 1990), and the Public Health Act of 1917 have been highlighted in this category [21, 22].

Between 1963 and 1990, Nigeria engaged in various international agreements, indicating its commitment to global standards and conventions related to the regulation of oil and gas exploration, production, and distribution. These agreements encompass the Mineral Oil (Safety) Regulations Act of 1963, Petroleum Regulations Act of 1967, Oil in Navigable Waters Act of 1968, Petroleum (Drilling and Production) Regulation Act of 1969, Oil Terminal Dues Act of 1968, Associate Gas Reinjection Act of 1979, Petroleum Amendment Act of 1973, and Harmful Wastes (Criminal Provisions) Act No. 42 in 1988 [21, 22].

The legislative framework for environmental protection in Nigeria spans a diverse range of regulations, including the Civil Aviation Act of 1964, the Antiquities Act of 1915 (1958), the Live Fish (Control of Importation) Act of 1965, the Explosives Act of 1964, the Territorial Waters Act of 1967, the Exclusive Economic Zone Act of 1958, the Petroleum (Drilling and Production) Regulations Act of 1969, the Nigerian Atomic Energy Commission Act of 1976, the Natural Resources Conservation Act of 1989, the River Basin Development Authorities Act of 1987, the Sea Fisheries

(Licensing) Regulations of 1992, the Quarries Act of 1969, the Land Use Act of 1972, and the National Parks Acts of 1991 [14].

Nigeria's environmental policy aims for sustainable development, ensuring access to a high-quality environment for every Nigerian. It emphasizes the conservation and utilization of natural environments, advocating for the preservation of essential ecological processes and ecosystems. The policy fosters active involvement from individuals and communities in enhancing the environment while advocating for collaboration on an international scale [23].

To implement Nigeria's environmental policy, six guidelines and standards address significant environmental concerns related to industrial practices. These include effluent limitations, water quality for industrial water uses, industrial emission limitations, noise exposure limitations, management of solid and hazardous wastes, and pollution abatement in industries. Despite these efforts, Nigeria's environmental protection is considered insufficient [24].

Water pollution is a widespread ecological issue in Nigeria, affecting both rural and urban areas. Industries, including petroleum, mining, wood and pulp, pharmaceuticals, textiles, plastics, iron and steel, brewing, distillery fermentation, paint, and food industries, commonly discharge waste into river ecosystems, impacting water quality and increasing water treatment costs. In urban areas, approximately 40 million people are at risk due to inadequate resource allocation, leading to waterborne illnesses and environmental degradation [25].

Nigeria's environmental policies exhibit significant fragmentation, encompassing a variety of legislation related to environmental protection. This fragmentation poses challenges to implementing comprehensive strategies, promoting fragmented processes, and increasing the risk of corrupt practices. However, during policy formulation, there was a lack of environmental knowledge among the general public, leading to a deficiency in mass-level environmental education and awareness initiatives. Rules were set without having readily accessible starting information from within the country, often depending on guidelines from the World Health Organization (WHO). This resulted in differences because of variations in society, economy, and climate [20, 26].

In the time of globalization spurred by information and communication technologies (ICTs), the Nigerian government wants to use these technologies to bridge information gaps. Despite these efforts, electronic waste (e-waste) remains widespread in Nigeria, aggravated by irresponsible disposal practices leading to environmental pollution [27]. The absence of a recycling or management policy for e-waste is a significant concern, especially considering the hazardous and toxic chemicals present in certain e-waste materials. This contrasts with the Electronic Waste Recycling Act in the United States [28].

A substantial portion of the annual 20–50 million tonnage of electronic waste is exported to developing countries like Nigeria, where the lack of legal, human, and technological infrastructure hinders effective management. Nigeria engages in the importation of electronic waste, often in the form of substandard second-hand ICT products that quickly become obsolete. Improper disposal of these products poses significant health and environmental risks, with plastics in electronics contributing to leaching into the environment. The uncontrolled discarding of electronic waste (e-waste) in Nigeria, involving processes like incineration and dismantling, creates notable environmental problems. These include concerns such as groundwater pollution, air pollution, and water pollution [28].

It's important to highlight that Nigeria doesn't have a specific requirement for a strategic environmental assessment (SEA), which essentially means applying the principles of environmental impact assessment (EIA) to policies, plans, and programs. The existing policies, despite their abundance, face execution challenges due to corruption, resulting in the inefficient use of resources. Consequently, there is a recommendation for a thorough revision of Nigeria's environmental protection policies, addressing obsolescence issues. Additionally, there is a need for the reorganization of implementation and monitoring agencies to enhance their performance. Law enforcement and anti-corruption agencies should undergo overhaul for more effective governance. Integrating environmental sustainability education into school and university curricula is crucial, accompanied by increased awareness campaigns addressing environmental pollution.

4 Conclusion

The present era grapples with formidable challenges arising from escalating environmental pressures attributed to human activities. The concept of sustainable development emerged in 1987 as a response to the intricate linkages between environmental conditions and the societal, health, and economic challenges faced by communities. Termed by the United Nations World Commission for Environment and Development, sustainable development is characterized as an approach to development that fulfills the requirements of present generations while safeguarding the capacity of future generations to satisfy their own needs. However, numerous policies exhibit outdated characteristics and are marked by fragmentation. Many policies were formulated without consulting an informed population or utilizing domestically generated foundational data, relying instead on adapted guidelines and standards from the United Nations, resulting in adverse effects on socio-economic and climatic disparities. The lack of public involvement in the policy conceptualization and execution process is apparent. There are notable deficiencies in environmental protection legislation regarding the clear delineation of roles and responsibilities among various stakeholders, encompassing vulnerable groups, civil society, corporations, scientific institutions, and communities. These deficiencies are noticeable in the Federal, State, and Local Government tiers, especially in the context of problems related to risk management. The existing legislation falls short in providing adequate provisions for obtaining financial and other essential resources, both from budgetary and non-budgetary sources, to support nationwide environmental programs. Additionally, the current legal framework lacks established protocols and designated responsibilities for conducting environmental risk assessments, as well as providing relevant risk intelligence and warning mechanisms for deployment across the nation's developmental landscape. Society members' engagement in environmental risk management is notably insufficient, with a significant absence of regulatory provisions addressing the training and acquisition of relevant knowledge for individuals involved in environmental conservation. Furthermore, the legal framework fails to establish measures ensuring the comprehensive fulfillment of responsibilities by diverse stakeholders, including governmental and non-governmental entities. It also neglects to address the protection of individuals' rights before, during, and after a catastrophic event.

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Environmental Conservation for Sustainable Agriculture

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Abstract Sustainable agriculture is an effective approach towards environmental conservation. While agriculture provides food and livelihood for millions of people it also contributes to deforestation, habitat loss, soil erosion, etc. Additionally, the sector is a significant source of pollution, with pesticides and fertilisers contaminating waterways and disrupting ecosystems. Agricultural expansion often leads to the encroachment of wild lands, driving down prices and contributing to poverty. To address these challenges, sustainable agricultural practices are essential. This chapter explains how cutting-edge techniques can help reduce agriculture's negative environmental effects and ensure long-term food production. These techniques include crop breeding, carbon sequestration, microbiome management, and climate smart irrigation. Reducing reliance on natural resources and using inputs more effectively are two ways to promote sustainable agriculture. Sustainable agriculture takes a holistic approach to farming by integrating three key objectives: social equity, economic profitability, and environmental health. By adopting these principles and leveraging technological advancements, the future of environmental conservation and sustainable agriculture looks promising. Environmental conservation is paramount for sustainable agriculture. We can reduce the damaging effects of agriculture on the environment while ensuring long-term food production and security by implementing sustainable practises, such as organic farming and climate-smart agriculture. Prioritising the adoption of these strategies is essential if we are to create an agricultural system that is resilient and sustainable for both the present and the future.

Keywords Sustainability · Sustainable agriculture · Environment conservation

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1 Sustainability

Agriculture is vital to human existence and, by extension, to all human activity. It consistently provides humans with the resources they need, including food, clothing, shelter, and other necessities for life. To satisfy all the above needs for a remote future without harming the environment, sustainable agriculture is an approach to sustainability. We can say that: "Sustainable Agriculture is a type of ecological and economical supportive practice that includes a coordinated system of natural processes along with the systemized uses of natural resources, non-renewable resources, and biological resources, including biological cycles and control".

According to another definition, sustainable agriculture is an "integrated system of plant and animal production practises with a site specific application that, over the long term: (a) satisfy human food and fibre needs; (b) improve environmental quality; (c) make efficient use of non-renewable resources and on-farm resources and integrate appropriate natural biological cycles and controls; (d) sustain the economic viability of farm operations; and (e) improve the quality of life for people" [1].

The principles of sustainable agriculture are:

(i) Coordination of biotic and abiotic processes in production of food and other agro products with various biological processes and interactions required for maintaining ecological balance towards sustainability.
(ii) Reducing the use of those materials, equipment, or energy sources that cause harm to the environment, consumers, as well as farmers.
(iii) Make prolific and efficient use of people's overall abilities to work in a coordinated manner to solve common ecological and economic problems of sustainability [2].

Earlier, during 1960 and 1970, agricultural sustainability was not an issue of concern; the people and government were more concerned about the productivity of food to prevent mass starvation for the growing population worldwide. Increasing food production was the only primary area of focus globally back then, which led to the very famous "Green Revolution." The Green Revolution concentrated on the industrial-scale production of food crops, especially wheat and rice, where soil erosion was not a problem. The increased use of synthetic fertilisers and pesticides (insecticides and weed killers) in various agricultural sectors and other human activities has resulted in increment of various environmental pollutants, such as air pollution, water pollution, soil pollution, and global warming, which has given rise to a greater emphasis on sustainability [3].

1.1 Agriculture as a Sustainable Industry

Agriculture must sustainably meet human needs not only today but also for the foreseeable future. To meet the long-term requirements of a population that is rapidly expanding, sustainable agriculture must now be industrialised. Nearly all of the industries around the world are dependent, one way or another, on the agriculture sector. For instance, agriculture is a major source of materials for the textile industry, the sugar industry, the vegetable oil industry, the newspaper industry, and many other industries.

The initiation and expansion of sustainable agriculture will result in resilient and high-productivity sustainable industries. Achieving the three main objectives of sustainable agriculture—social, economic, and ecological sustainability—will ensure economic growth while promoting economic sustainability. A sustainable food system and industrial and commercial agriculture are only two components of the development of a sustainable economy. “Sustainable agriculture systems function with relatively small, profitable farms that use fewer farm inputs, coordinate the production of both plants and animals, have a proper ratio of rich biological diversity, emphasise high yielding and smart technologies, and rely on environmentally friendly, economically viable renewable energy sources.”

Sustainable systems rely less on the inputs of synthetic and chemical based substances and give less weight to economically productive techniques that shift the cost of the environment onto society. The wellbeing of people and the health of the ecosystem would both improve if more farms adopted sustainable agricultural methods. A productive and sustainable food system would imply integrated and direct relevance between farmer and consumer, which would entail more increased straight trade of foods to local consumers (through green markets, farmer communities, etc.) These localised trade strategies and tactics result in reduced food transportation distances from the farm to the kitchens, using minimum energy in the process (Fig. 1). All other raw materials, from those used in agriculture to those used in industry, can be transported using the same method [4].

1.2 International Agriculture Research Centres and Their Focus of Research for Sustainable Agriculture

The term “sustainable development” was first used in the 1987 Brundtland Report by the World Commission on Environment and Development, which defined it as “development that ensures that the needs of the present are met without compromising the ability of future generations to meet their own needs.”

Present day concerns with the sustainability of agricultural ecosystems around the world have made remarkable cognizance of the need for the use of agricultural natural resources. For effective and efficient utilisation of soils and plant or animal products, along with the genetic material, many research programmes and development policies have been laid down by various International organisations like CGIAR and GFAR [5].

Until after World War II, there was minimal international cooperation in agricultural research. In 1971, the Consultative Group on International Agricultural

Fig. 1 Sustainable agricultural perspectives

Research (CGIAR) was formed, which gave a vision for how improvement in agriculture can be achieved with international effort. Many of the problems identified cannot be solved by CGIAR institutions or through agricultural research alone.

Along with CGIAR, there are various other very popular international organisations supporting sustainable agriculture, namely Central Arid Zone Research Institute- Indian Council for Agricultural Research (CAZRI-ICAR), International Crops Research for Semi-Arid Tropics (ICRISAT), International Livestock Centro International De Agricultural Tropical (CIAT), International Institute for Tropical Agriculture (IITA), Centro De La Papa (CIP), etc. A development strategy involves the dynamic interaction of agricultural and non-agricultural sectors and focuses mainly on sustainable agriculture. The International Service for National Agricultural Research, meant to assist national agricultural research programmes, provides an opportunity to encourage research from a sustainability perspective [6]. The main areas of focus towards the research for Sustainable Agriculture are Environment and Agriculture Interaction (through ecosystem and agro-ecology services); Innovation of Nanotechnology and Nano-fertilisers; Micro-biome for Sustainable Agriculture; Implementation of Climate smart Agriculture; Production of Plant growth resources (PGR's); Finding new Agriculture techniques for emission reduction; Implementing Nitrogen efficiency through crop management and Carbon sequestration; Promoting Gene editing and genetic modification strategies etc.

2 Sustainable Development Goals

Massive efforts have been made to increase agriculture's ability to produce food and ensure food security since the 1996 World Food Summit (WFS) [7]. In 2015, as a follow-up to the Millennium Development Goals (MDGs), the first supranational development agenda ever proposed, the international community established a new set of goals and targets that should guide every nation's actions for a better world. These were called the Sustainable Development Goals (SDGs) as shown in Fig. 2.

All aspects of sustainability are covered by the Sustainable Development Goals and the 17 SDGs include developed countries as well, whereas the MDGs only addressed developing countries [8]. This is because global cooperation is required to achieve prosperity without jeopardising the integrity of the planet's natural boundaries.

The United Nations 2030 Agenda for Sustainable Development (SDGs) lists 17 Sustainable Development Goals (SDGs) that deal with resource consumption, climate change, hunger, health, and other issues in order to ensure the wellbeing of the global economy, society, and environment. In order to limit trade-offs and achieve the SDGs, a comprehensive and integrated approach is required because of the interdependence and multidimensional nature of these problems, which can have both positive and negative effects [9].

Agriculture is a significant industry that is advancing the SDGs. Investing in agriculture is regarded as essential to eradicating hunger, reducing poverty, and enhancing health. The 2030 Agenda for Sustainable Development established metrics to measure sustainability based on each of its pillars, and several SDGs have a direct

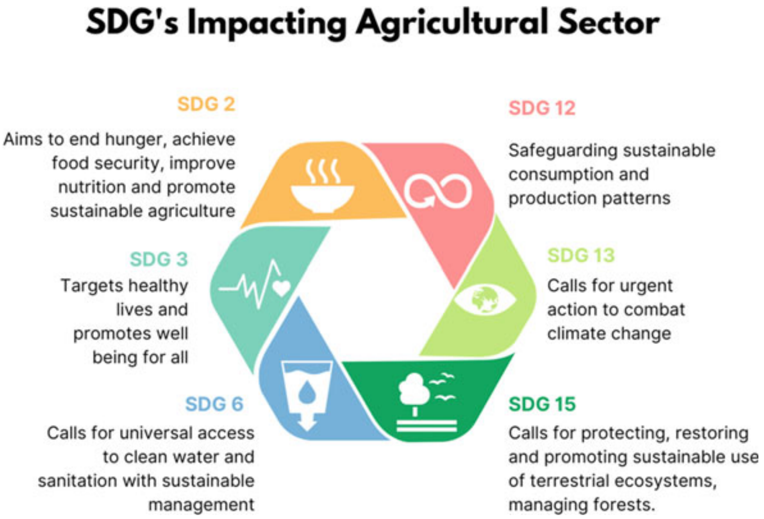

Fig. 2 SDG's linked to agricultural sector

connection to agriculture. The Fig. 2 highlights SDG's linked to the agricultural sector.

Even though considerable efforts have been made over the past few decades to create strategies and policies aimed at achieving global food security, approximately one in ten people worldwide are currently dealing with severe levels of food insecurity [7]. As the world's population grows, ensuring food security has become a critical concern. Despite being effective for producing large quantities of food, conventional farming methods pose serious risks to the sustainability of the environment because they use too many resources, cause pollution, and degrade biodiversity [10].

These problems are addressed by sustainable agriculture, which supports methods that are socially just, economically viable, and environmentally responsible. Precision farming, GM crops for higher yield and disease resistance, and the incorporation of renewable energy sources into farming practices are some examples of cutting-edge technologies that can be used. In order to preserve ecological balance and ensure food production, sustainable agriculture also encourages the use of regional resources and traditional knowledge [11].

2.1 Environmental Conservation and Sustainable Agriculture

Agriculture and the environment are closely connected. The main challenge facing the agricultural sector is providing food for a growing global population while minimising environmental effects and protecting natural resources for the future [12]. Achieving sustainable agricultural development is essential since this industry has the potential to have a very significant impact on the environment for future generations.

For more than 10,000 years, agriculture has shaped human societies and the natural landscape of the planet. Humanity began to exert substantial control over its environment during the early Neolithic Revolution, also known as the period of simple agriculture and livestock rearing [13]. The introduction of agriculture commenced the development of composite societies due to greater population densities. However, because of their intensive agricultural methods, ancient agricultural societies frequently experienced issues with their water supplies, soil degradation, and deforestation.

Another significant outcome of the agricultural industrial revolution was the Green Revolution, which began in the middle of the twentieth century [14]. During this time, a rise in food production was accompanied by an increase in environmental problems due to the widespread use of high-yield crop varieties, fertilisers, pesticides, and irrigation (Table 1). Nitrous oxide, a potent greenhouse gas, was released into the atmosphere and waterways due to improper and persistent fertiliser use [15].

Table 1 Environmental impact throughout agricultural history

Period of time	Important agricultural developments	Effect on the environment
Ancient times	Farming, hunting and livestock rearing	Localised ecosystem disruptions
The Ancient Civilizations (8000 BC–AD 500)	Ploughs, crop-rotation, and irrigation technology development	Deforestation, elevated land use, and soil erosion
Middle ages (500–1500)	Better ploughing techniques and 3-field crop rotation	Elevated land use and improved soil fertility
The Industrial Age (1750–1900)	Automatization and the use of synthetic fertilisers	Runoff and degraded soil contribute to water pollution
Modern era (20th–21st century)	GMOs' introduction and the Green Revolution, sustainable farming methods and precision agriculture	Increases in yield come with losses in biodiversity, contaminated water, and degraded soil. Potential for less environmental impact

To address these issues, integrated and comprehensive strategies that take into account agriculture's multifaceted functions in supporting livelihoods, maintaining ecosystems, and providing food are needed, such as sustainable agriculture [11, 16].

According to the FAO, sustainable development in agriculture, forestry, fishing, and other related industries "conserves land, water, plant, and animal genetic resources, is environmentally non-degrading, technically appropriate, economically viable, and socially acceptable."

Sustainable agriculture practices include the integrated management of natural resources with technologies, policies, and procedures that support farmer profits, fulfil human food needs, enhance environmental quality, and enhance life quality for all members of society. Contrary to conventional agriculture, sustainable agriculture prioritises the use of renewable resources, places a high priority on local soil fertility, and maintains a balanced cycle of nutrients and energy in the soil. Additionally, it emphasises preserving biodiversity, upholding crucial ecological functions, and minimising waste and energy use [17].

3 Sustainable Agriculture Strategies

Agricultural production continuously experiences unexpected confrontations. Despite a huge increase in the food supply over the previous 50 years, 8.9–14.3% of people still experience hunger and malnutrition, respectively. The agriculture sector is threatened by factors such as the rapidly growing global population, rapid climatic change, and a lack of arable land. A significant impact on the atmosphere is caused by the expansion and intensification of agriculture. The atmospheric changes will have an influence on the safety of the supply of food around the globe [18]. In order

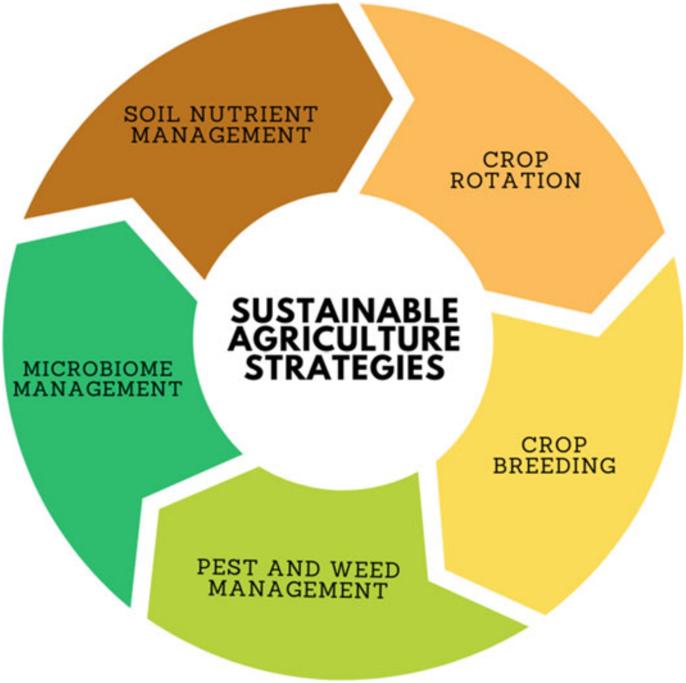

Fig. 3 Sustainable agriculture strategies

to increase the yield, maximising the use of chemical fertilisers and pesticides ultimately causes eutrophication and habitat destruction; other side effects can include the extinction of species, loss of ecosystem balance, etc. [19]. This also contributes to consequences such as global warming, further leading to a maldistribution of rainfall (in some areas floods and in some drought conditions), eventually leading to negative effects on crop growth and increasing the risk of plant diseases [20]. To overcome all these challenges, as shown in Fig. 3, it is necessary to design crops that promote sustainable agriculture, providing food security for an ever-increasing population while minimising deleterious effects on ecology [21].

3.1 Soil Nutrient Management

Fruitful agriculture relies on solid soil nutrient administration practices [22]. Decisions regarding nutrient management are consequently made after taking into account how accessible nutrients are to crops. Ion transport to plant roots is caused by soil nutrient adaptability. The soil test ensures that crop nutrient requirements and soil nutrient supply capacity are quantified. The next step in the nutrient management plan is to decide on the optimal nutrient rate, appropriate nutrient source, most effective nutrient placement technique, and timing of nutrient delivery [23]. For crop productivity to meet consumption demand, efficient management of soil nutrients becomes absolutely essential, which indirectly reduces the influence of nutrient usage on the environment. Agronomists study how to apply fertiliser to crops in the optimum way to get the highest yield, which could be influenced by climate and genotype. This has dominated research on plant mineral nutrition over the last two centuries [24].

The soil's ability to supply nutrients fluctuates constantly. The nutrition cycle is referred to as the continuous processing of soil nutrients into and out of the soil. Due to intensive farming and excessive use of chemical fertilisers and pesticides, Indian soils have become nutrient deficient and poor in organic matter content. As a result, per capita land availability is decreasing. One of the finest approaches for farmers to deal with nutrient management is the assimilation of organic and inorganic nutrients [22].

3.1.1 Integrated Nutrient Management

The principle objective of integrated nutrient management (INM) is to merge the existing and de-novo techniques of management of nutrients into eco-friendly and economically sound farming practices that focus on the sensible and proficient usage of organic and inorganic sources of nutrients. INM focuses on performing the finest nutrient cycling by maintaining the harmony between nutrient requirements by the crop and the release of nutrients in the soil, lowering harmful effects such as leaching, run-off, and immobilisation, further promoting nutrient recovery by crops, and finally sustaining maximum crop yields in different cropping systems, securing the long-duration viability of the system. As per the long-duration manure studies, the insertion of organic manures catalyses the soil-quality index, thereby contributing to the complete up-gradation of physical, chemical, and biological traits. The "life of soil" is said to be its organic content. Thus, the integration of organic residues and inorganic fertilisers can be considered a wise approach to maintaining soil fertility [25].

3.2 Crop Rotation

Crop rotation is an agricultural practice that helps to increase the production of different crops on the same land, thereby increasing their yield while minimising pests and crop diseases. While removing the negative consequences of the existing continuous crop techniques, crop rotation can help crops adapt to a specific climate change. Crop rotation success depends on wisely adopting a crop rotation method that can adjust between crop viability and environmental effects. Crop rotation is vital in many national strategies such as food security, environmental development, etc. [26].

Diversified crop rotation can be defined as a system of multiple rotations of several crops. Bowles emphasised the point that diversified crop rotation can efficiently enhance soil health while simultaneously interrupting the cycle of herbivores and weeds and reducing soil borne pathogens [27]. One of the most important methods for ensuring sustainable agricultural output is diverse crop rotation, which helps in the development of farming systems all over the globe.

Crop rotation has the ability to increase productivity by replacing crops periodically, thereby replenishing the nutrients in the soil. Crop rotation with different kinds of crops helps reduce production risk and enhances soil fertility for a longer duration, thereby benefiting the farmers. Crop rotation has the potential to bring up nutrients from deeper layers of soil, as seen in the case of deep rooted crops when grown alternatively with fibrous rooted crops. This helps in the better extraction of nutrients from all soil layers, which otherwise would be eliminated from the system. For e.g.: legumes fix atmospheric nitrogen fixation, and the available nitrogen can be used efficiently by future crops with high nitrogen requirements [28].

3.2.1 Impact of Crop Rotation on Agriculture and Environment

Crop rotation upgrades the soil's structure by improving its physical and chemical properties, thereby increasing its resistance to soil erosion. It has the ability to enhance soil enzyme activity, ultimately contributing to good health of the soil. Crop rotation can effectively resist extreme climatic conditions such as droughts and floods, reducing the damage to agricultural crops. Crop rotation promotes the number of beneficial microorganisms in soil, ensuring crop growth and quality improvement [26]. Crop rotation enhances soil nutrient content, including total nitrogen and organic carbon, and maintains the strength of the soil structure. It also increases crop disease tolerance [29].

CROP ROTA-A crop rotation model—It is a convenient tool for the approximation of classic crop rotation. Based on previous land use information and agricultural standards, it develops typical crop rotation from farm level to regional level. A case study application provides the practicality of Crop-Rota to support integrated land use modelling. The flexible nature of Crop-Rota for various regions and geographic scales makes them universal. Local expert knowledge can be used to determine the agricultural criteria [30].

3.3 Crop Breeding

Conventional crop improvement techniques may not be completely efficient in providing a food supply to the ever-increasing population [31]. To preserve the harmony between food production and food demands, there is a need to develop new strategies while protecting the environment. One of these approaches can be crop breeding, which focuses on achieving high yield, maintaining yield stability, achieving the best grain quality, and increasing nutritive value while simultaneously decreasing the use of chemicals and fertilisers and water consumption, contributing to the overall protection of the environment. Crop breeding can be defined as the science of inserting desirable characteristics into the plant to increase nutritional values as well as high productivity withstanding extreme climatic conditions and crop diseases [32]. A synchrony between new agricultural practices and recent advancements in breeding technology enables the usage of genetic resources to design and insert the desired novel genes or alleles into the crop [33].

3.3.1 Strategies to Attain Crop Breeding

Crop breeding can be achieved through several strategies. First and foremost, traditional breeding techniques alter the plant's genes indirectly by crossbreeding standard crops with crops containing targeted traits. The most advanced method is genetic engineering, which transfers a specific set of required genes between crops. Several genome editing technologies that alter the plant genome in an accurate and anticipated manner have been developed [34]. Homing-End Nucleases (HEs/meganucleases), Zinc Finger Nucleases (ZFNs), CRISPR-associated short palindromic repeat (CRISPR-Cas), and Transcription Active Nucleases (TALENs) are some of the best examples [35]. Relative speed and efficient tracking of genes are possible. Hence, crop varieties with the necessary genes can be efficiently developed [36].

Crop breeds developed may be considered as smart crops, which are capable of adapting themselves to different climatic changes. This can only be possible through intense exploration of genetic resources while simultaneously understanding the plant's mechanisms to respond to various biotic and abiotic ecological conditions. These crops exemplify novel and unique crop varieties far better than the existing ones [37]. Mutagenesis-based breeding has produced about 3000 marketable varieties of food crops [38]. By using various physical, chemical, and biological methods, we can produce new artificial alleles with the help of random mutagenesis [39]. The development of Mutagenesis requires the screening of a huge population for the identification of mutants possessing desirable characteristics. This makes the process time-consuming as well as labour-intensive, specifically for polyploid crops [6].

The first tobacco mutant was produced in the 1930s. Since then, induced mutations have become one of the critical tools in crop breeding for genomics that is functional in plants and model organisms. Targeting Induced Local Lesions IN Genomes (TILLING), a novel reverse-genetic technique, is used to create stable populations of mutant crops such as Arabidopsis, tomato, barley, soybean, and wheat. All of these technologies collectively assist us in crop breeding by taking into account both agriculture and the environment.

Developed nations often follow modern agriculture (High-input systems), which focuses on high yields and profit but leaves behind a fundamentally unstable environment. This often leads to a decline in available natural resources. Low input systems emphasise effective management of on-farm resources, which results in a more sustainable agro ecosystem. This also includes low-energy inputs such as gas and oil, unlike the high-input practices of modern agriculture systems [40]. Altogether, crop breeding can be done more successfully and efficiently by combining crop breeding with genome prediction strategies interlinked with machine learning and artificial intelligence.

3.4 Pest and Weed Management

Pests are the creatures that cause the destruction of crops, leading to a decrease in yield and thereby a decrease in human health and environment. These could be in the form of insects, plant pathogens, rodents, nematodes, etc. Weeds are generally undesirable plants that obstruct the growth of required crops. Their presence in the field can have several negative impacts, such as biodiversity loss, loss of potentially agricultural land, less grazing, etc. They account for nearly 45% of total loss of crop production. One of the major obstructions in the development of sustainable agriculture are weeds, as they control several crop cultivation practices. Hence, it becomes mandatory to develop novel crop production systems that should be eco-friendly, energy-saving, profitable, and encourage rural community development. Radical research in weed and pest ecology helps us create weed and pest control strategies that are beneficial for not only farmers but also the environment [41].

The manual method of weed management is exceptionally prominent. But in recent times, human labour has become not only costly but also unavailable. One of the strategies to reduce heavy dependence on synthetic herbicides and agrochemicals is the integration of allelopathy with agriculture. This involves various techniques such as allelopathy in crop rotation, mulch, green manure, cover crops, intercropping, etc. [42]. Intercropping becomes one of the most significant approaches as it helps the system utilise the available resources in a much more efficient manner when compared to monoculture. This in turn decreases the quantity of resources for the weeds to grow and also decreases dry weed [43]. Intercropping proved to be beneficial for plants such as wheat + gram maize + soybean/black gram, sugarcane + green gram/black gram, sorghum + cowpea to control weeds [44]. To attain sustainable agriculture, it becomes necessary to enhance the weed-suppressing ability of crops. Integrated weed management produces ideal crops with the collaborative use of specific knowledge, prevention strategies, monitoring procedures, etc. Integrated weed management also focuses on improving the efficiency of herbicides or preventing herbicide application with other mechanical or biological methods.

Pest management can be achieved by using an agro-ecological approach, which highlights the embodiment of ecological principles in pest management while ensuring higher harvests and also being advantageous to farmers conserving the environment. This technique focuses on biological processes that promote agro-ecological crop protection. This involves reforming the crop production system to induce ecological measures that prevent the organisms from becoming pests. This is usually a long-term pest management method [45]. An outstanding approach for managing both pests and weeds is Crop Rotation. This strategy helps to control different insect pests, protect crops from diseases and weeds, maintain soil health, and ultimately produce sustainable and eco-friendly crops. It helps prevent *Cuscuta epilinum* (linseed), parasitic weeds including *Cuscuta campestris* (niger), Striga sp. (mainly in sorghum and maize), Orobanche (Brassicas and solanaceous crops), and crop-associated weeds *like Echinochloa colona/crusgalli* (in rice), Avena sp., and *Phalaris minor* (in wheat). Integrated pest management principles are based on the sustainable use of pesticides in agriculture [46].

Bioherbicides are microorganisms or phyto-toxins obtained from microbes, insects, or plant extracts used to control weeds [47]. Biopesticides or biofertilizers are prepared by using living organisms or their products, such as bacteria, fungi, nematodes, protozoa, viruses, and beneficial insects. There are now reasonably priced options for bacterial infections, weeds, and pest insects [48]. Important characteristics of bio pesticides are target-specificity, environmental conservation, biodegradability, and convenience in integrated pest management programmes. Bio pesticides can protect crops from pests in an environmentally friendly way while posing less of a risk to human health. *Bacillus thuringiensis* is one of the most widely applied microbial biopesticides.

3.5 Microbiome Management

Microbiomes are plant-associated microorganisms that have the potential to overcome many challenges in achieving sustainable agriculture. Besides microbial functions in crop production, efficient use of resources, biopesticides, and biofertilizers, research has been carried out to understand their useful characteristics in improving crop performance [49]. The word "microbiome" refers to the collective genetic material of all the microbes (both biotic and abiotic) that are present in a certain environment [50]. The phytobiome includes different kinds of related microorganisms such as bacteria, viruses, fungi, protozoa, etc. [51]. The microbiome of plants contains a pool of genes and is associated with many functions, including pathogen protection, nutrient procurement, abiotic stress tolerance, and regulating the host immune system [52].

New strategies for controlling the plant microbiome for its advantageous characteristics based on existing and potential manipulation techniques are:

(i) microbiome introduction and engineering
(ii) the host plant's breeding and engineering
(iii) selecting agricultural methods that change the soil's environment in a way that benefits the local microbial communities.

In the rhizosphere, there is a large amount of plant growth-promoting rhizobacteria [53]. Pathogens emerging from soil constitute a constraining element in the quality and productivity of crops [54]. The rhizospheric microbial community is often modulated by environmental perturbations such as floods, salinity, etc. A rhizospheric microbiome of plants can be managed by several strategies that can be central to stress mitigation and disease management [55]. In agricultural environments, soil microbes, composed of bacteria, archaeas, fungi, viruses, and other microbial eukaryotes, play an important role in the biogeochemical cycle of nitrogen (N), the maintenance of soil fertility, and the effectiveness of N use in plants [56]. In the context of microbiome management, there is a need to figure out which microbes are affected by crop practices and whether they carry particular qualities [57]. Significant antagonistic interactions, such as those between microbes and host plants to combat phytopathogens and host plants to attract protective rhizospheric microbiomes and enhance microbial defence mechanisms to eradicate phytopathogens in the rhizosphere [58]. Therefore, the management of microbiomes in the soil becomes of utmost importance for attaining sustainable agriculture.

4 Environmental Conservation Strategies

The environment includes the interactions between biotic and abiotic life (i.e., climate, weather, and natural resources), which can alter both the human race and their economic status [59]. Due to an increase in population, there is a greater need for food and resources, which has resulted in environmental degradation and overuse of resources. Hence, conservation of the environment has become an important aspect. New conservation methods have been implemented, which include Carbon sequestration, soil conservation, waste management, and climate-smart irrigation. But these advanced technologies alone cannot solve the environmental crisis because the main cause of the problem lies in human behaviour. The awareness of proper management technologies among humans can help minimise waste production, resulting in less environmental damage [60].

4.1 Climate-Smart Irrigation

The change in climate pattern due to anthropological activities such as soil, water, and air pollution is known as climate change [61]. Due to these climatic changes, it is necessary to introduce technological innovations that are used to increase agricultural yields while conserving the environment. One of the techniques includes climate-smart irrigation, a part of climate-smart agriculture [62].

Due to demand for water from various sectors and degradation in water quality caused by water run-off, wind erosion, and irregular rainfalls as a result of climatic changes, the availability of water resources on agricultural land has become a serious threat. Climate-smart irrigation helps in the watering of crops at certain times, which reduces the excessive flow of water compared to other agricultural practices. It also helps to provide nutrients in the required amounts. The excessive use of groundwater has decreased the water level in the soil but can be maintained by using climate-smart irrigation technologies, which maintain the soil's integrity by protecting it from soil erosion.

This method is mostly employed in water-scarce regions, which helps manage the water utilities and decreases the removal of nutrients from the top layer of soil. This technique is used to increase water productivity and provide rural income for farmers to build a community and overcome their losses from drastic climate changes [2]. These irrigation and water management techniques also help mitigate climate change. But unstable land tenure systems, a high initial cost, and a lack of knowledge and training are some of the barriers to adopting climate-smart irrigation technologies, mainly in rural areas [61].

4.2 Soil Conservation

Soil is defined as a natural, non-renewable source that is composed of living and mineral materials [63]. Agricultural practices such as ploughing and tilling have become a major source of land degradation, which reduces the fertility and productivity of soil; hence, the necessity of conserving the soil has become an important aspect as it not only affects the quality of food produced but also climate change, environmental conditions, etc.

4.2.1 Factors Affecting Soil Erosion

The major reason behind soil degradation is soil erosion, which is caused by various factors such as water run-off, wind erosion, alkalization, acidification, ploughing, and tilling. Due to water run-off, the top layer of the soil gets washed away, thereby leaving fewer nutrient-containing layers for the production of crops, which results in a low yield. Later, these nutrients migrated or washed away to different water bodies along with harmful contaminants such as pesticides and fungicides, resulting in the contamination of water. And due to deforestation and land distribution, the temperature of the land increases, making it lose its soil moisture, resulting in soil erosion. In croplands, if the crop residues are not burned down or are not incorporated into the soil, the temperature of the soil can be maintained, preventing soil erosion. Sustainable techniques can't be used to eradicate the soil erosion problem completely but are used to restore and manage the degraded soil [64].

4.2.2 Soil Conservation Methods

There are different methods for conserving soil, thereby eliminating the serious threats caused to the environment.

Crop rotation: In agricultural lands where continuous cultivation of one particular crop can produce a desirable yield, it also depletes the nutrients present in the soil, which reduces the yield and soil fertility to minimal levels. Rotation of various kinds of crops not only provides higher yield but also provides optimum conditions for the replenishment of nutrients [65].

Contour ploughing: This is the process that helps reduce the effects of floods and storms by reducing soil erosion and controlling water erosion by infiltrating enough moisture into the soil.

Microbial fertilisers: The relationship between plants and microorganisms helps to conserve the environment sustainably and increases socio-economic values by promoting the overall development of organic agriculture. Microalgae, Rhizobium, Azospirillum, Mycorrhiza, etc. help to improve soil fertility, the quality of food produced, and also increase resistance in plants towards disease and pests [66]. Soil microbes produce various kinds of enzymes such as beta-glucosidase, phosphatase, and urease, which act on various organic matter existing in the soil and provide nutrients for the plant's growth [67]. This method is mostly employed in water-scarce regions, which helps manage the water utilities and decreases the removal of nutrients from the top layer of soil.

4.3 Waste Management

Municipal solid waste is the major byproduct of our lifestyle and is increasing much more rapidly than our own lifestyle [68]. Most of the waste produced is non-degradable, which raises issues for both mankind and the environment and risks the future of our own planet [69]. The management of various kinds of waste produced is done by waste management, which includes the collection of waste, its transportation, and its processing. The whole concept of waste management is to reduce waste production and dispose of the waste without causing any harmful effects to the environment or society, and it urges us to recycle the matter to reduce the waste produced.

A large amount of waste is produced in different forms, i.e., solid, liquid, and gaseous, from different sources, and the disposal of these wastes depends on their nature [70–72]. Various types of waste and their treatment can be observed in Table 2.

4.3.1 Technologies of Waste Management for Conservation of the Environment

Many urbanised countries, such as the USA, China, and India, are the largest solid waste producers. Disposal of this waste is very necessary as it can pollute the environment and be hazardous for the human population [73].

Table 2 Types of waste, their effects and treatment

S. no	Types of wastes	State	Effects	Treatment	Examples
1	Biological waste Solid waste	Solid	Impacts on human health Soil and groundwater pollution Emission of Toxic gases	Landfills incineration, and composting	Items, containers, food scraps, yard waste, and inorganic waste, both durable and non-durable
2	Agriculture residue	Solid and liquid	Air pollution. Decrease bulk density of soil	Incineration and conservation tillage	Silage effluents, antibiotics, crop residues, straws, and oil pits
3	Pulp and paper waste	Solid and liquid	Air, water, and soil pollution contribute to chlorine bleaching Paper emits toxic methane gas	Aerated Ponds activated sludge	Bark, Leaves, needles, branches, sludge, and black liquor
4	Industrial waste Heavy metals Cu, Zn, Mo, Ni, Pb, Hg, Cr, Cd, Au, Ag	Solid	Carcinogenic	Adsorption Ion-exchange, Pyrometallurgy, Hydrometallurgy	Waste batteries and X-ray films
5	Wastewater effluents	Liquid	Water pollution	Coagulants, inorganic salts, sewage treatment	Pesticides, detergents, hydrocarbons, oils, etc.
6	Construction waste	Solid	Environment Pollution Loss of Natural resources	Recycling waste management plants	Timber, metals concrete, mortar, brocks, etc.
7	Radiographic film	Solid	Hazardous to the environment by releasing silver	Combustion technology acid leaching process	Dental films, etc.
8	Electronic waste	Solid	Release of toxic metals, chemicals air pollution	Recycling incineration	Electronic devices and hardware equipment

Various methods used for waste management include land filling, incineration, recycling, coagulation, and composting. Landfilling is the process of dumping waste products that can be recycled onto the surface of the soil or into the oceans. These waste products are categorised and dumped in different fields. Industrial waste constituents include asbestos, ash, etc. and are dumped in monofils; hazardous waste is dumped in secure landfills to avoid leakage of toxins into habitable environments; and bioreactor landfills are the advanced technology that helps to manage the waste in a short period of time using few resources.

Composting is an advantageous, cost-effective, and eco-friendly waste management technique. Due to lack of land for dumping waste, composting has become an important waste disposal method. It is generally an aerobic process that degrades the organic matter in presence of oxygen, but if the waste is compactly packed during composting, it leads to anaerobic degradation, producing odour [74].

The coagulation technique is used to treat water and waste, and coagulants used are dependent on the nature of waste being disposed of. Alum is the cheapest and most widely used coagulant; other polymeric coagulants are also used [75].

Incineration is used to degrade hazardous waste produced by medical, industrial, and construction sectors, etc. This method is used to decrease the volume of toxic waste by reducing toxicity levels, but it leads to emission of various chemicals into the environment. Unregulated incineration produces waste gases such as carbon dioxide and vapours; the maximum levels of atmospheric carbon concentration lead to environmental pollution. Pyrolysis is a chemical incineration method that is used to degrade organic materials by heating them in the absence of oxygen. It produces volatile gases and fuel oils [76].

Biogas, the organic waste, is degraded anaerobically, producing methane and carbon dioxide in smaller quantities. These gases can later be used as biofuels for gas turbines and engine boilers, as well as to synthesise a few chemicals [77].

4.4 Carbon Sequestration

Most of the carbon present in the atmosphere is in the form of CO_2, which is about 0.04%. But due to the enormous emission of CO_2 from various sources such as greenhouse gases, transport, industries, etc., there has been an increase in environmental pollution [78]. Hence, technologies have been developed in order to reduce the rate of atmospheric CO2, which include carbon sequestration [79].

The process of storing the excess atmospheric carbon dioxide is known as carbon sequestration. Carbon dioxide can be captured and stored in various kinds of geological sites, i.e., oceans, soil, other biotic regions, etc.

4.4.1 Types of Carbon Sequestration

CO_2 can be stored in many ways by carbon sequestration, which is of two types: geological carbon sequestration and biological carbon sequestration [80].

Geological carbon sequestration: As the name suggests, it is stored in various underground boulders or rocky formations such as mesas, etc. The CO_2 has been converted from a gaseous state to a liquid phase and has been introduced into these rock-like formations. This type of trapping is done by trapping mechanisms that include hydrodynamic trapping, solubility trapping, residual trapping, and mineral trapping [81]. This type of sequestration process helps to form oil wells that can be used for future generations.

Biological carbon sequestration: It is a type of storage process involving the capture of CO_2 in various biological sites such as agricultural lands, croplands, and vegetation. Afforestation of lands can also decrease the rate of CO_2 as it will be utilised by the plants in photosynthesis [82]. But afforestation of one particular area cannot solve the emission issues of the whole world, and afforestation of such a large area is difficult to approach [83].

4.4.2 Soil Carbon Sequestration (Croplands and Agriculture)

Croplands are known to be the largest carbon sequestering lands, with the help of crop residues. But tillage and burning down the residues of croplands can become the largest source of emissions [5]. In order to reduce these emissions, soil carbon sequestration must be employed, but this may challenge the carbon levels in the soil. Soil carbon sequestration is an advantageous process, but it isn't a permanent solution as it is a riskier protocol, and the carbon storage by this process can only last for a few decades.

Soil carbon sequestration will not be helpful for direct emission reduction, which can lead to emission gaps. But carbon sequestration in soil helps in increasing carbon levels, but only if it is measured and verified, and thereby helps in increasing soil fertility.

It also helps in nutritional improvement, thereby increasing the quality of food and reducing damage to the environment. Soil carbon sequestration has helped to improve environmental conditions and society, and the quality of food consumed has also increased [84].

Nowadays, the distribution of land is a rapid process. Agricultural lands are being dissected, and their carbon input is decreased by emissions. Lately, research has helped to design and improve technologies that help to regenerate the carbon in the soil by increasing the input of organic matter on agricultural land [5].

Even though many direct carbon sequestering methods have been in use for sequestering carbon, these methods are insufficient; hence, direct carbon mitigation can also be a useful tool. Here, the carbon dioxide produced by the burning of fossil fuels is used as a source to grow photosynthetic autotrophic organisms. These organisms produce eco-friendly products such as biofuels, biochemicals, animal feed, etc., thereby helping in the conservation of the environment [85].

5 Challenges

The three biggest challenges that have created adverse side effects in sustainable agriculture are.

5.1 Population Dynamics

Population dynamics is the study of the population depending upon size (whether it's increasing or decreasing), sex ratio (male and female sex ratio within the entire population), and age (how many people of different ages are present within that population). How population dynamics affect sustainable agriculture: With the growing human population, the usage or utilisation of water resources has also increased, resulting in a lack of water supply in the agricultural industry, which leads to a substantial loss of agricultural productivity [86]. According to recent surveys, it has been estimated that 27% of the 482 of the world's biggest cities have 233 million people, and the demand for available water resources by the growing population has increased exponentially [87]. In India, a large human population in 19% of cities completely depends upon water for their survival as well as to fulfil their daily needs, which results in lack of water supply across agricultural and urban sectors. Recent studies say that Jaipur, located on the north-west side of India, is going to face massive water scarcity by 2050. The major components responsible for elevating food demands are: growing human population, the development of the big industries, better living standards, and the production of better sources of income among the growing population by the working class in developing countries. It's considered that by the end of 2050, the demand for food will rise by 60–98%, which would become one of the biggest threats to sustainable agriculture and have a massive impact on the agricultural sector [88]. As the population size is gradually increasing, the demand for agricultural land by the public is also increasing [89], which further leads to the massive declination of the surface area of available agricultural land, which will later affect agricultural productivity [90]. An increase in human population size leads to an elevation of the density of overall people on the given agricultural land, because of which agricultural productivity gets reduced, and there is the development of a nonequilibrium state between population density and remaining agricultural area.

Population density has an inverse relationship with land carrying capacity:

$$\mathrm{P} \propto 1/\mathrm{LCC}$$

where, P = population density
LCC = Land carrying capacity.

When population density increases over agricultural land, land carrying capacity of that land will start to decrease gradually, which leads to a sharp decline in crop productivity. The three most important factors that will increase population density by decreasing the land carrying capacity are: Rapid population growth, immigration, and urban area condition.

5.1.1 Food Sufficiency

As demand for food is rising, food availability is declining at a rapid rate. Around 62.7% of paddy yield is responsible for rice production, 100 g of rice contains 130 kcal of energy, and each person needs 770 g of rice /day which amounts to a requirement of 1000 kcal of energy per day. The requirement of individuals for the available food is spontaneously escalating, and the availability of food is rapidly declining, which is gradually leading to a substantial loss of agricultural productivity. An interesting case would be Pontianak city (which is located in west Kalimantan), where the higher rate of population density led to a materialistic-orientation of land resources, which will further affect the massive area of agricultural land. The migration of people from one place to another mainly depends on pull and push factors. The regions with good industrialization, trade, education, residence, and transportation are the pull factors for human beings. Whereas poor infrastructure, bad education facilities, and unhygienic environmental conditions are push factors. The pull factors have a direct relationship with the rate of immigration, whereas the push factors have an inverse relationship with the rate of immigration [91].

5.2 *Climate Change*

Climate change is the result of long term changes in weather patterns over a particular period of time [92]. Elevations in man-made activities like industrialization, urbanisation, and deforestation together lead to the production of more green-house gases and a rapid rise in the rate of climate change, which leads to the sustainability of overall agricultural lands.There are three methods by which green-house gases can easily affect sustainable agriculture: An increase in the level of Carbon-dioxide will affect the growth rate of crops and weeds; Carbon-dioxide persuade changes in the climate will completely alter the rate of condensation and temperature levels, which will later affect the productivity of plants and animals; and an increase in the sea level further results in massive losses of farmland and elevates the salinity of groundwater in coastal areas.It has been estimated that the productivity of the agricultural sector around the world will observe a decline of 3–16% by 2080. In developing countries, climatic conditions are average, which is why they are above the crop tolerance level;

this will result in a substantial declination of agricultural productivity by 10–25% by 2080, but in rich countries, agricultural productivity is increased by 8% because of a reduced climatic condition as compared to agricultural productivity in developing countries [93]. India is one of the developing countries where agricultural productivity faces a massive decline from 30 to 40%. Since the ancient period, India's agriculture has completely relied on the monsoon season. According to studies, it has been revealed that over the past few decades, there has been a rapid rise in temperature in the Indian climatic conditions [94]. Similarly, changes have been noted in the high rainfall pattern of the Indian climate [95], which is why agricultural productivity is directly affected by sudden climatic changes and weather patterns [96]. India is still facing a high frequency of extreme climatic conditions; there have been 23 high scale drought events between 1891 and 2009. The frequency of these high scale droughts in India is still rising [97]. It has been found that the majority of cultivated land lacks irrigation facilities [98]. In Rajasthan (located in the north-western part of India), pearl-millet production almost declined by 10–15% due to a rise in temperature of 2 °C. States like Jharkhand, Chhattisgarh, and Odisha are facing huge losses in rice production because of drastic drought conditions. It is projected that there will be a massive decline in the agricultural productivity of the majority of crops by 2020, and by 2100, it will be around 10–40% because of a rise in condensation temperature and a fall in water irrigation.

The major and adverse effects of climatic change will impact rain-fed agriculture, which covers almost 60% of the cropland. During winter, when the temperature increased by 0.5 °C, the wheat productivity of the rain-fed agriculture decreased by 0.45 tonnes/acre all over India [99].

Food productivity is completely dependent on climate change; the variations that take place in temperature and humidity will directly affect crop productivity, which in turn affects the amount of food produced. Drastic climatic conditions like floods and droughts lead to massive losses in crop productivity and leave large areas of arable land uncultivated, which has become a major threat to nutrition security. The effects of global warming have remarkable outcomes that not only affect agricultural productivity but also increase the risk of starvation among people. The number of people suffering from long-term starvation has increased from 800 million in 1996 to one billion in recent years. According to the United Nations population data and projections, they have estimated that the overall worldwide population is going to increase by 2.2 billion by the year 2050. As the size of the human population increases, it will lead to a huge and substantial loss of the agricultural sector, which enhances the feeding problems around the world.

5.3 Deforestation

Deforestation refers to the transformation of forestland into permanent non-forest land use for agricultural purposes, grazing, and urban expansion. There are two main

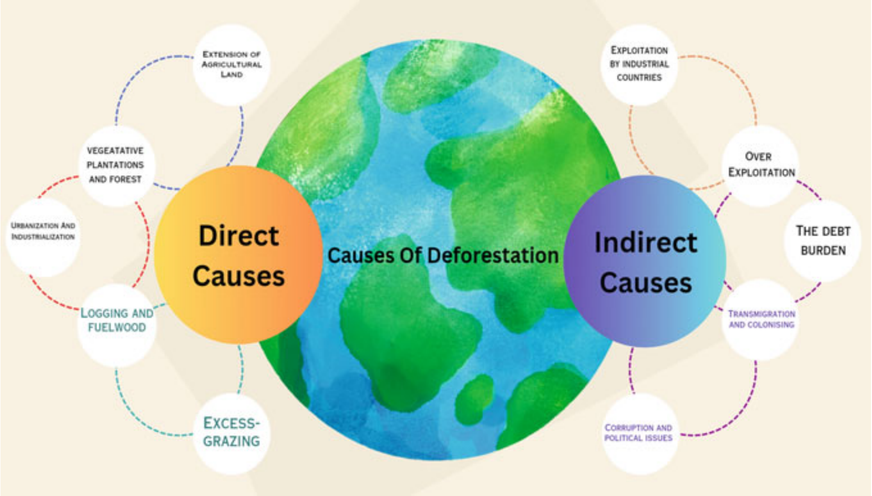

Fig. 4 Causes of deforestation in sustainable agriculture

causes of deforestation affecting sustainable agriculture: Direct causes and In-direct causes as shown in Fig. 4.

5.3.1 Effects of Deforestation

The major effects of deforestation on sustainable agriculture are.

Reduction in soil and water resources due to floods: Deforestation is one of the major factors that leads to substantial destruction of the water cycle at a global level [100]. There are different types of water resources that are completely disrupted due to deforestation, like fisheries, drinking water, marine inhabitants, drought and food control, crop damage, water irrigation systems, and salinization, which further contributes to the problem of soil erosion [101]. Deforestation is the main reason behind the draining of rivers and streams, which result in downstream flooding, and this leads to soil erosion in forestland areas. Deforestation is also behind soil compaction, where soil particles are densely packed with each other and the uptake of moisture by soil particles gets reduced, which leads to topsoil erosion and faster flooding of forestland [102].

Biodiversity and habitat loss: Tropical rain forests act as one of the major sources of biodiversity richness, but deforestation and forest land degradation not only disturb the Biodiversity but also destroy the Biodiversity of migratory and endangered species (species that are at the stage of extinction). The major loss of Biodiversity in forest-associated areas leads to irreversible and destructive changes in forestland ecosystems. An alternative consequence of deforestation is to increase conflicts between humans and animals, which results in a declining success rate of forestland conservation. The elephant habitat, which is located in the northern region of West Bengal, is one of the largest biodiversity hotspots, suffering from a high level of Fragmentation [8, 103].

Economical losses: Each and every year, there is a substantial loss in tropical rainforests, which leads to massive loss in the forest's capital of approximately 45 billion US dollars [104]. Deforestation, forestland degradation, and overexploitation of natural resources lead to potential loss of future income and employment.

Social outcomes: When civilians immigrate from their native place, there is a massive level of forestland degradation and overexploitation of natural resources due to changes in their traditional lifestyles in ancestral areas. The arrival of outsiders results in the destruction of traditional lifestyles and belief systems, which are going to be aggravated by infrastructure development such as construction of roads, buildings, etc., which leads to the expansion of borders and frequently results in socio-land conflicts [105].

6 Outlook for the Future

The United Nations formulated strategies to achieve sustainable agricultural development by 2030 in 2015. Despite these efforts, the latest WHO data shows poor sustainability progress. The data reveals that over 800 million people worldwide, approximately one out of every nine individuals, still suffer from food shortages [106]. To tackle these challenges, it becomes crucial to boost overall grain production and increase bioenergy, particularly ethanol, which is expected to rise significantly by 2030.

However, these advancements also pose multiple challenges, including reduced agricultural manpower, shrinking arable land areas, water resource scarcity, and the impacts of climate change. Population imbalances and generational shifts have significant repercussions for rural agricultural labour and farm management. Moreover, the diminishing arable land faces limitations for specific lands because of environmental and geological necessity. Additionally, climatic crises affect a wide array of crops, leading to the potential exacerbation of everlasting ecological concerns such as peat loss, soil aridification, groundwater depletion, and floods. The disparities highlighted above illustrate how advanced technology and sophisticated approaches enhance both productivity and ecological sustainability on the farm. In its current situation, it is anticipated that integrated structures like artificial intelligence and big data capabilities will make sure to make the agriculture sector a progressive one. These integrated structures will encompass a diverse range of agricultural support from the beginning of seed sowing to the end of yield. Emerging technologies like telemechanics, virtualization, agricultural robotization, and big data have the potential to bring a new era to farming. The following techniques and tools are essential for promoting ecologically friendly farming for future generations.

6.1 Wireless Telephones, the IoE [Internet of Everything] Leads to Transmission

Smartphones are the wireless gadget, and the Internet of Everything (IoE) makes it facile to solve problems that arise in the agricultural profession by facilitating a market that offers to solve adversities. These technologies extend across the people of urban and rural areas by making it possible to blend them under one roof and making sure that potential growers are reached to a great extent [107].

Presently, users can access a wide range of devices to disseminate comprehensive information. Moreover, smartphones and the IoT have gained widespread popularity and are increasingly interconnected through expanded smartphone networks. This interconnectedness enables the collection and processing of vast amounts of data, which can significantly benefit agricultural farming [108].

Additionally, it supports the premises of social connections through devices for exchanging and seeking information and learning things from it, which improves farming and connects its community. As these technologies are rapidly expanding, this will have a better impact on future farmers [109].

Low power wide technology assets include multiple elements, such as predicting weather situations, prior detecting diseases and pests that can be cleared at an early stage, handling of energy, helping to reduce food waste by examining the transportation of goods, examining the quality of air, observing the movement of wild life, aiding smart irrigation, and the sensors also level of soil humidity and warmth, which helps farmers optimise the conditions of their farm and enhance yield.

6.2 Intertwining IoTs and Wireless Sensors

The idea of merging IoTs and wireless sensors is an innovative step that facilitates farmers in recognising the health of crops, fertilisation, outbreaks of diseases, patterns of weather,data analysis for trade, remote monitoring where the GPS continuously renews data, and quality of yield, thus minimising product loss [110].

6.3 Drones and Robots

Drones came into play to build sustainable agriculture by conserving the environment. These drones play a part in multiple agricultural tasks, mostly spraying water, solutions of nutrients, and fertilisers from a high altitude, which in a short time covers most of the parameters. Currently, drones with 3D cameras and sensors recommend farmers take the precise steps required to raise yield. Robots are especially advantageous as they potentially help lower the manpower required, cut down on costs, and save a lot of time [111].

6.4 Machine Learning (ML)

Machine learning merging with artificial intelligence made possible endless possibilities where the genes of the seeds were improved and conserved with high productivity and shared with the farmers, wherein the growers could sow high yield seeds and enhance the productivity of crops. Furthermore, the algorithms of machine learning submitted evidence to recognise market obtainability and compare market prices [112].

6.5 Nutriculture and Multilevel Farming

It is understood that most of the arable land and natural wealth have been depleted because of urbanisation, which has made many scientists work on and improve on varied techniques, namely Nutriculture, which is popularly known as hydroponics, and multilevel farming. The yield can be cultivated with fewer resources than the land needs, and these techniques require less labour and provide higher yield. Most developing countries are progressively changing towards these methods of creation.

Furthermore, the adoption of smart grids and microgrids dealt with the adversities of attaining sustainable agriculture and conserving ecology. The support from individuals boosts great innovative methods, a secure environment, and an abundance of natural wealth for successors [113].

To preserve natural wealth and resources and make the environment safer for upcoming generations, sustainable agriculture is a great approach. Sustainable agriculture's goals are to attain continued fruitfulness, economic feasibility, and recovery of agricultural systems. This chapter includes some strategies to attain sustainable agriculture, such as crop rotation, soil nutrient management, crop breeding, weed management, and microbiome management that result in environmental conservation. By using these strategies, fertility, soil health, soil biodiversity, high yield, and microbial communities are strengthened in the soil, and the use of synthetic fertilisers and chemicals is reduced. However, there are many challenges to attaining sustainable agriculture. Mainly, farmers face a challenge because of financial issues, sudden changes in their way of life to sustainable practices, and the minimal knowledge that they possess in regards to them. Furthermore, existing policies and market structures may not adequately incentivize sustainable practices. Climatic conditions can also be a major challenge because of their unpredictable impacts on yield production. Irrespective of the challenges faced, sustainable agriculture will be a promising solution for the next generation. Scientific research and present-day technology are setting innovative strategies for sustainable agriculture. Safer and sustainable agricultural practises can be quickly implemented to contribute to the improvement of the environment by overcoming the various difficulties and accepting the prospects for sustainable agriculture in the future.

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Environmental Conservation for Rural and Urban Development

Srinivasan Kameswaran, Bellamkonda Ramesh, and Manjunatha Bangeppagari

Abstract In terms of economy, society, and the environment, both urban and rural regions are interconnected. One of the main sectors where there are strong links between rural and urban communities is ecological services. The careful investigation of a variety of empirical as well as theoretical research forms the basis of this essay. The many advantages that urban and rural regions receive from their connection are examined from the viewpoint of ecological services. The major goal was to clarify how using ecological services in rural regions might improve rural–urban connections. Usually, urban expansion cannot be imagined alongside rural development, particularly in areas where farming is the main sector. Rural areas are necessary for the existence of urban areas. Urban regions acquire nearly every aspect of their ecological services from rural regions. To meet their needs for nourishment, drinking water, timber, supplies of raw material, etc., since they are essentially byproducts of rural ecological services, urban regions depend on rural areas. It is important to acknowledge the benefits that urbanization offers to rural communities, including improved mobility to markets, agricultural supplies, employment possibilities, and more. Effectively planned "rural–urban" connectedness is necessary, according to the principle that growth in urban areas should not have any influence on the availability of services provided by rural ecosystems or rural living. To guarantee the long-term sustainability of assistance, rural region ecology requires being preserved, and rural residents should draw the attention of the government to the ecological benefits that these areas provide.

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1 Introduction

More people live in cities now than ever before. Approximately all of the individuals on the planet will reside in urban areas by 2050 [1]. Urbanization rates in developing nations like India are substantially greater than the worldwide average. This does not imply that growth in urban areas should only be given a narrow focus. There won't be a fix for the issue of ensuring food safety if rural growth is not given enough consideration. Accordingly, given the continuous fast rate of growth in urban populations and physical expansions, achieving urban growth through rural growth should be a policy priority.

It is incorrect to consider urban and rural regions to be independent spheres. The growth and expansion of one region depend upon the other's growth since the two spaces are interdependent. The larger populations, particularly those in rural areas, benefit from the wider changes brought forth by urbanization. On the other hand, rural growth advantages metropolitan regions as well as rural ones. Due to the connections between output and expenditures that exist [2], this is crucial. As a result, rural–urban links are a viable strategy for achieving national development.

In the context of urban growth, "rural–urban" interconnection is especially significant; in particular, the connection is critical to urban development. The growing rate of urbanization is causing metropolitan regions to face a number of problems, including metropolitan poverty, a shortage of space, increasing costs of food, as well as an insufficient supply of drinking water. In this situation, a strong rural–urban connection has a greater chance of minimizing these urban area concerns.

According to many sources [3–5], rural–urban connectivity is increasingly crucial for rural growth, lowering poverty rates, and transformations. Rural–urban linkages' crucial influence on urban growth is frequently disregarded, while rural ecosystems' contributions to urban growth are underappreciated.

This chapter's theoretical basis is the idea that while rural–urban linkages are crucial for rural regions, they also help urban regions. Ecosystem services are one area where urban and rural areas can interact. Ecosystem services are the different tangible and intangible things people get for free from our surroundings, all the result of natural procedures such as those involving raw materials, water, forests, environments, etc. The ecological services observed in rural regions need to be sustainably improved, as well as services must be provided to rural communities in order to receive advantages in exchange for their services, in order to strengthen the linkage. The fundamental tenet is that ecosystem services are not distributed equally between both urban and rural regions [6].

Greater regional aspects of ecological services make them a vital connection among both urban and rural regions. The main means of demonstrating "rural–urban" connectedness is by encouraging specific natural resources. Explaining these natural resources along with the way they help to connect these distinct locations is essential to fortify and preserve the connectivity.

This chapter's main objective is to investigate how, to the mutual benefit of both, ecological benefits could increase the interdependence within cities and rural regions.

What ecological services provided by rural areas are therefore needed by urban places? How does the growth of urban and rural regions alike benefit from these environmental services? When the ecological services of rural areas aren’t present, can urban places survive? What positive effects might these ecological services have on the rural–urban link? They served as the foundation for this systematic chapter.

It is nearly universally acknowledged that rural and urban populations cannot coexist without being mutually dependent on one another. To strengthen ties between rural and urban areas, the government and relevant organizations must work to preserve and protect village ecological amenities and build the necessary facilities needed to move country goods to metropolitan markets.

2 Rural–Urban Connectivity Theories

Numerous political, ecological in nature and socioeconomic factors impact all concepts related to cities and rural areas. Nonetheless, a lot of academics as well as politicians believe that urban areas are home to densely populated areas while rural areas are sites where residents cultivate [7]. The fact that both agreements are handled differently may be due to this specific point of vision. It may also downplay the part that each place has played in bringing about the eradication of austerity in the two regions. In actuality, the population densities and accessibility of social services differ significantly among urban and rural areas. In contrast to metropolitan areas, where many people live in a condensed amount of space with improved and increased access, rural areas are where residents live in remote areas with inadequate access to social services. The gap decreases as rural areas relocate more near urban centers. Apart from this, it would be hard to provide a simple explanation for differentiation, particularly when it comes to the numerical distinctions among the urban and rural regions. This point of view will become evident when examining the percentage of the impoverished living in rural areas of developed and rising countries. “Alkire et al.” [8] conducted research spanning 105 nations and found that whereas 28.6% of the poor live in developed countries, 86% of the impoverished do so in the countries of sub-Saharan Africa as well as South Asia. This proves beyond a doubt that the global average of impoverished people residing in rural areas does not particularly represent developed nations. Many big contrasts between the urban and rural regions in emerging nations. Both urban and rural regions generally differ from one another in terms of poverty and infrastructure. Compared to their urban counterparts, rural residents in many developing nations lack access to basic social services [7].

3 The Three-Magnet Hypothesis

Both urban as well as rural areas offer a variety of amenities. Things that are cheap in the country are expensive in the city, and whatever is abundant in the city is rare in the countryside. According to Howard [6], this is the primary reason for the disparate lifestyles that exist in both rural and urban settings. Due to the distinct advantages and drawbacks that each lifestyle provides, people often struggle to decide between rural and urban living. “Howard’s three-magnet” theory states that rural regions are superior to urban areas in terms of natural beauty, air quality, water availability, and housing costs. Rural areas, however, suffer from low incomes, a lack of entertainment, long walking distances, and low levels of public morale. However, when it comes to communal possibilities, work opportunities, the potential for greater salaries, and the number of entertainment places, urban areas outperform rural ones. Additionally, they are at a disadvantage due to their greater costs of living, increased slum areas, and isolation from nature [6]. To solve the dearth of possibilities in rural locations and establish the foundation for a more prosperous, cooperative, and liberated human experience, a change is thus necessary. The three magnets hypothesis states that there should be a location that can be considered both rural not urban but instead has social opportunities, a lovely view of the outdoors, affordable rent and decent wages, conveniently accessible fields, bright homes, and vegetable gardens, and also without slums as well as polluted air.

4 Connections Between Rural and Urban Areas

Urban–rural connection is essential to the socioeconomic development of the urban as well as rural inhabitants. Rather than isolating urban and rural locations, it might be crucial to take into account their interactions. “Rural–urban” relations might be viewed from two perspectives: spatial links that integrate citizens, products, and funds, as well as knowledge, and economic relations that integrate Industries, services, as well as farming [9]. Rural activities taking place in urban centers and urban activities taking place in rural areas can also be considered relationships between both urban and rural regions. The urban food chains, environmental relationships encompassing ecological services, socioeconomic status relationships that include more direct supply chains, and governance linkages that integrate rural as well as urban governing bodies in a democratic and participatory way are further ways to conceptualize the idea of rural–urban linkage [10]. Environmental services are frequently produced by a complex interaction with natural phenomena like solar power, which aid in the operation of the ecosystem, which is home to all life [11]. These numerous ecosystem-related benefits can be broadly categorized into four areas, according to Gomez-Baggethun and Barton [12]: providing, regulating, sustaining, and cultural services.

4.1 Services for Provisioning

Provision facilities are those that provide things that come straight from the environment, such as nutrition, drinking water, timber, as well as fibers like cotton and wool. These solutions are essential to most rural as well as urban populations. According to Jennings et al. [10], rural areas supply metropolitan areas with food, drinking water, electricity, raw materials, and other environmental services.

4.1.1 Provision of Food

The world's urban population has increased rapidly, from "746 million in 1950 to 3.9 billion in 2014" [13]. Nowadays, more than half of the world's population lives in cities. Precise projections indicate that around 2050, there will be "2.5 billion more urban" residents worldwide, or 66% of the total population [13]. Urban areas would see a sharp increase in their food needs due to population growth, fast urbanization, and rising incomes.

Among the 60 percent of the planet's cultivable land that is located in rural regions, roughly seventy percent of the food that's consumed globally is produced [14]. For the purpose of making money, the vast majority of those foods get sold to markets in urban areas. Many cities completely depend on rural regions for their food supply, albeit the extent varies [15]. Urban areas are going to require an increasing amount of food to meet the demands of their inhabitants due to the rapid urbanization taking place in urban regions around the world. Agricultural cultivation in rural regions could be impacted by this. As a result, the dilemma is how to feed the expanding and wealthier metropolitan population. Food production and related activities have a higher potential in rural locations. Despite their connections in the social, environmental, and economic spheres, rural and urban regions differ from one another when it comes to farming for food [10]. Improved facilities, infrastructure, and efficient administrative processes are needed to transport food from rural to urban regions. The farmers trying to supply urban demand for food face significant obstacles in a number of developing nations due to a lack of infrastructure, such as roads [15]. Building the infrastructure required to link rural areas with metropolitan markets is crucial for the provision of food. A variety of regulations must be established to guarantee that small-scale farmers can fully contribute to fulfilling urban food demand. In addition, the following basic prerequisites must be met in order to enhance food supply in order to meet urban dwellers' nutritional needs: (i) Enhancing retail and wholesale sectors; (ii) placing wandering traders in lower-income neighborhoods; (iii) permitting permitted information about markets to be disseminated for more effective production as well as marketing options; (iv) protecting the ecosystem from pollution; (v) providing sufficient water to sustain agriculture production; (vi) enhancing the infrastructure for transportation for more effectively access;

To ensure that urban areas receive an adequate and excellent supply of food, the standard of the connections between urban and rural areas must be raised and reinforced. To strengthen the link between urban and rural regions in the food supplies, and lessen the physical effects of urban growth upon crop productivity and efficiency. Due to the lack of a comprehensive land use plan, urban centers in most developing nations frequently encroach on agricultural areas [17]. The other objective of the rural–urban connection is to support enhanced market access for farmers who produce food. Urban marketplaces in cities, small, and medium-sized cities are where the majority of worldwide agricultural producers in rural regions access the market [18]. Rural as well as urban regions will be affected by these developments, which also have an impact on regional socioeconomic growth and the security of food. The other possible markets for farmers in rural regions are those for livestock goods. Oil from vegetables, sugar, and livestock goods (beef, milk, and eggs) is being consumed at an accelerated rate due to rising incomes and worries about food that provides energy. According to Proctor and Berdegue [18], dairy products, eggs, and meat are collectively 29% of the total amount of food consumed in underdeveloped countries whereas 48% in wealthy nations. Given the accelerated rate of urbanization in metropolitan regions, this proportion is expected to rise. For rural farmers, the following conditions increase the benefits of connecting urban and rural places' food supplies.

- Contemporary markets as well as fast food restaurants will tend to expand spatially in urban regions. Farmers who grow food in remote regions may have greater market possibilities as a result of this.
- In contemporary markets, where food costs might be more costly and agricultural producers from rural regions will benefit additionally, all three primary, secondary, and tertiary phases of processing food will be introduced.
- Innovations in market chain procurement procedures will take place as specialized and dedicated buyers visit rural regions where agriculture is grown. This lowers the cost of doing business for rural food growers.
- A combined packaging, grading, preparation, transportation, and logistical system is needed for contemporary food systems. Through the creation of jobs, these developments have a favorable impact on rural communities. Stronger rural–urban connections along with intensive flows of individuals, resources, and goods through the rural–urban interfaces are characteristics of urbanization around the globe. As an example, according to the prognosis for the flow of remittances [19], remittance flows among rural and urban regions in developing nations have increased dramatically.
- The contemporary processing system enables food processing businesses to look for outside markets where the products might fetch a greater price. As a result, a lot of food producers will see a rise in the price of their goods and an increase in demand. For example, over 21,000 farmers and over 340 dealers profit from the annual sale of "13,000 tonnes of cowpeas" grown in Burkina Faso's farming regions, which are meant for both export and the country's capital city [18].

- The conventional markets whereby farmers may develop their social and human capital along with city people shall also alter.

Therefore, farmers need to boost the quality as well as the quantity of their food supply as a way to obtain an advantage in urban marketplaces. Additionally, the policies must be changed in order to better satisfy the demands of urban and rural populations, primarily by highlighting the advantages of rural–urban connectivity in urban as well as rural regions.

To increase the production of food in rural regions, the network known as Sustainable Development Solutions has recommended three ways. As follows.

- Improving the productivity of soil, energy, nutrients, and water used for the generation of high-yield crops. This will result in nutrient-dense meals with little food waste and losses.
- Forest preservation, wetlands conversion to farming land, soil resource protection, and ensuring that agricultural operations are adaptable to natural calamities and climatic changes.
- Facilitating easy access to essential infrastructure (water, land, transportation, modern energy, mobile, and internet connection, inputs for farming, and consulting services) in rural regions (Fig. 1).

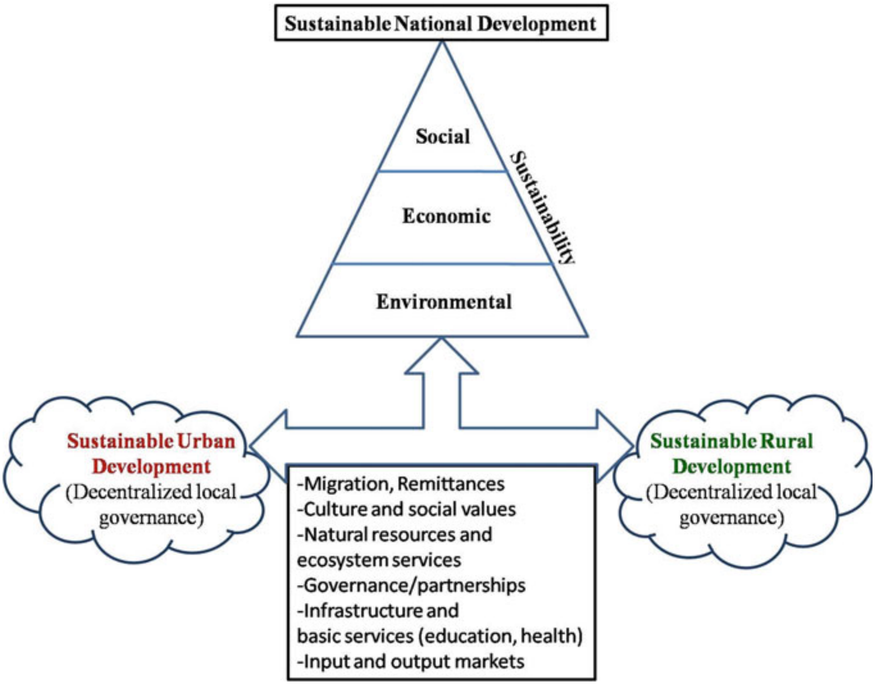

Fig. 1 Sustainable urban–rural links conceptual framework

The second crucial factor to take into account for the benefit of the rural–urban interface is concentrating on infrastructure amenities that may enhance rural–urban connectivity. There is solid proof that improving access to both urban and rural regions through roads has a positive impact on agriculture productivity as well as output. In India and China, agricultural productivity has raised as a result of governmental funding for highways that link urban and rural regions, as reported by [20].

4.1.2 Water Supply

A highly vital component of health is water. To regulate physical functioning and control the temperature of the body's drinking water is crucial. Everyone needs to drink enough water every day, despite the fact that there are various variables, such as temperature, daily activity, and health concerns. For healthy digestion and to avoid dehydration, it's necessary to drink enough water. Another essential resource for sustainable urban and rural growth is water. Family consumption, utilization in agriculture, utilization in industry, recreation, and a key ecological function all depend on it. However, providing enough water and avoiding pollution have proven to be difficult problems. Currently, around half of the world's population lives in urban areas. Urban regions in emerging countries will grow at the fastest rate in future decades. Urban areas are growing rapidly, which will strain the ecosystem along with challenging problems with organizational and social evolution, growth of infrastructure, as well as regulation of pollution. According to the WHO [21], "844 million people" worldwide have no access to a minimum drinking water service, making up about "2.1 billion" people who have no access to an updated water supply. Water scarcity is expected to affect two-thirds of the world's population by 2025 [21]. Occasional increases in water demand are brought on by the rapid urban population growth. According to a UNDESA [22], more than 789 million urban inhabitants lack access to a better water supply. According to similar sources, this amount goes up by nearly 6 million every year. The other difficulty in providing water is the abundance of slums in metropolitan areas. Because they lack access to clean water and sanitary facilities, many residents of these sprawling urban areas are vulnerable to infections. They also have to deal with huge amounts of pollution caused by the industrial as comfortably as urban operations in the peri-urban areas surrounding it, which release harmful chemical pollutants towards the nearby rivers [7]. Water resource management and sustainable water supply become crucial given the growing number of urban residents and the depletion of freshwater supplies. In order to improve ecological services and provide superior drinking water supplies, it is necessary to encourage the mutual dependence of both urban and rural populations. The mutual dependence on rural–urban" connections concerning ecosystem services has to be strengthened because of the growing urban demand for rural resources like water [7]. When city growth is defined by the spreading of city limits towards rural regions to meet rising numbers of people and increasing amounts of commercial activity, the relevance to this "rural–urban" nexus will become the greatest. Water is used for a variety of purposes in urban environments, most notably for residential, commercial, and industrial uses. There will be more demand placed on water supplies as metropolitan areas expand quickly. Numerous studies have thus focused on some instances associated with water diversions and reassignments “from rural to urban regions” [23]. National laws and policies contain a number of generally followed rules and regulations that govern how water is used [23]. Water allocation is therefore prioritized in urban regions. This problem is a significant one, especially in metropolitan settings where water is scarce. Where water needs to be transferred from possibly rural areas to metropolitan areas, either novel or modified facilities for water delivery need to be built. Urban planning, engineering work, energy requirements, and distances to urban areas all need to be taken into account in this situation. Furthermore, it is imperative to specify the desired application of water delivery, encompassing drinking, industrial, irrigation, and sanitation.

Around the world, there are many metropolitan areas close to waterways. This is because water serves as a commodity that spans the gap between urban and rural areas due to its large geographical proportions. The environmental implications of this could be substantial for ecosystem services and water systems. metropolitan and rural communities are more dependent on each other for water resources because of the potential upstream and downstream effects of the water infrastructure designed to supply metropolitan areas with water [7]. Water is extremely precious in metropolitan areas, therefore decisions about water resource management must consider long-term plans for dividing available water among rural and urban regions. Also, an opportunity to push in the planned transfer of drinking water “from rural to urban” usage in some cases, with the reasoning that water is often allocated by commercially inadequate, less-yield (farming) utilizes and that water transfers to greater effective “high-return” (cities) utilizes might boost overall financial stability [24]. Although this point of view is somewhat debatable, it is important to emphasize the proper balance of water “between urban and rural areas” for the benefit of the national economy and the welfare of society. Water was moved from rural to urban regions in the Burkina Faso instance of Ouagadougou. 70% of the water used in Ouagadougou, Burkina Faso’s major city, comes from rural areas [23]. Gefersa and Legedadi are Addis Ababa’s two main water sources in India, providing a significant amount of the capital city’s water requirements. Ecosystem services are beneficial to both urban and rural inhabitants and usually have a major influence on the availability of water in a rural–urban linkage. According to Jujnovsky et al. [25], the ecosystem service in Mexico City contributes significantly to the water supply because it provides 18.4 hm^3 of potable water annually, which supports 78,476 people and has the potential to benefit 153,203 people. The demand for drinking water will increase due to the rapid rise of city people, and it might be necessary to transfer water from urban to rural areas. Freshwater-related changes in policies as well as capacity planning will therefore be needed to lessen the negative consequences of moving water “from rural to urban” areas. Fundamental reforms are required to reduce the potentially harmful consequences of drinking water diversions to rural residents. These significant policy reforms should include the creation of protected rights to water to consumers, the decentralized distribution of water utilization duties to the appropriate phases, and the utilization of benefits, among them offering changes especially in urban settings, along with financial markets via convertible ownership, along with the adoption of suitable technologies for water conservation [26].

4.1.3 Availability of Raw Supplies

To create goods and render services, untreated natural substances are employed. Both finished and semi-finished items can be made from these raw components. Agricultural products are among the primary sources of raw materials from rural regions, and these items can be utilized to create things including cotton, food, and beverages. As a result of the broader range of economic benefits it provides, rural resources are becoming more and more significant. If these resources are utilized wisely, they can significantly alter how rural communities can flourish sustainably. It has to be recognized, therefore, that these constitute rural investments, accessible to all, primarily for the benefit of rural communities. Resources in rural areas should be thought of as countryside capital to help improve sustainable development [27]. Industrial and allied institutions with a reliance on agricultural raw materials are concentrated in urban regions. The industrial utilization of all these farming ingredients will enhance farm income and provide jobs in resource utilization, raw material processing, and new product development, thus revitalizing rural economies. More money can benefit the urban economy by allowing farmers to invest more in rural economies and farm maintenance. Rubber from nature is utilized in the production of several outcomes as well as various common rubber-based goods such as hoses, belts, shoes, surgery supplies, as well as rubbery textiles. The majority of natural rubber production is sold in foreign markets. The consumption of natural rubber has increased significantly worldwide over the last thirty years [28]. The way that natural rubber is used in industrialized and developing countries differs as well. The consumption of natural rubber is higher in developing nations than it is in industrialized nations [28]. This is partially a result of developing countries experiencing urbanization at a significantly faster rate. The other agricultural commodity that connects rural and urban communities is vegetable oil. The primary vegetable oils available for purchase on the global market are rapeseed, palm, soy, and sunflower oils. The majority of applications allow for the substitution of these oils for one another. Industries mostly employ these products to create foods and other goods. Another significant agricultural commodity used to make sugar is sugarcane. Sugar is a common ingredient in the foods we eat every day. In addition, companies use it extensively to create other goods. The desire for sugar is the main driver of sugarcane agriculture. The other key factor influencing sugarcane production is the quickening growth of ethanol demand. Although agricultural crops including sugarcane, corn, wheat, sugar beetroot and cassava may all be fermented to make ethanol, sugarcane accounts for the vast bulk of ethanol production [29]. Positive effects include the removal of lead compounds and harmful petrol fumes. Because it is a renewable fuel, it also helps combat “global warming” by reducing the quantity of carbon emissions that cars emit.

Feeds for plants and animals are another essential farming ingredient for businesses that operate in cities. Agriculture is the practice of growing food and rearing livestock. In rural regions, farming produces unprocessed food, feed, fiber, and other necessities by raising domesticated animals and certain plants. These goods mostly benefit businesses that process food. Around the world, the food processing business is growing. The phrase "food processing industries" describes a collection of commercial operations entailing the processing, preservation, and packaging of food items for distribution. Processing foods refers to the methods and techniques required to transform raw agricultural resources towards food fit for consumption by humanity. The production of food processing ranges from large, heavy on capital, highly automated factory operations to small, labor-intensive, conventional family-owned companies. Many nutritional enterprises source their raw ingredients nearly exclusively from local fishery or agriculture [30]. Clean, harvested, or slaughtered ingredients are used in food processing to create food products primarily for urban markets. With the growth of industrial food consumption, the food industry became a dominant business segment with endless opportunities for job development [31]. This remarkable contribution from rural communities supporting the growth of agriculture-related enterprises in cities is noteworthy. Even while an entire rural region produces farming output, certain urban cities serve as the center of agricultural trade with neighboring rural regions. According to study "by Roberts et al.". [32], agricultural enterprises make a significant contribution to the metropolitan regions that are immediately around them. Contrarily, farm households will profit from spatially concentrated agricultural transactions as a result of the regional agribusiness consolidation. According to research by Roberts et al. [32], selling to agricultural-related companies greatly boosts farmers' economies. Harrison [33] also asserted that the rural economy is significantly impacted by industries associated with agriculture. Thus, farmers will have more money to spend on agricultural supplies that will help them produce more food. Therefore, governments should focus on raising rural agriculture's productivity and output, which would also have the added benefit of expanding the chances for industrial activity in cities.

4.1.4 Wood Supply

In global urban markets, wood is an industry that is growing at the fastest rate [34]. Here, small-scale farmers stand to gain the most from selling extremely valuable timber and related goods to industry either alone or via intermediaries. Preprocessing, milling to make semi-finished goods, supplying niche markets that industrial-scale companies cannot effectively fill, and awarding contracts for specific tasks in forest-based sectors are the key market potential for timbers from village regions [35]. Currently, around "1.2 billion" small-scale farmers depend on farming plantation plants for their livelihood (Baker et al., 36). However, a lot of organizations, including policy directives, exclusively place a focus on large-scale natural forests [35]. Consequently, the primary barrier to the effective utilization of forest goods from agricultural regions is the reformulation of legislation that may assist small-farm producers [35]. Urban areas use forest products for firewood, and building materials, along with industry necessities including furnishings for homes and offices. For developing countries, access to timber and related goods is essential. This is in part due to the escalating rate of construction growth and rising energy demand. The procurement of fuelwood is extremely minimal in rural locations. Those who are not farmers make up a modest percentage of rural consumers who buy fuelwood [37]. Fuelwood and charcoal will be consumed wherever there is urban growth. Due to the possibility of an oversupply of fuelwood and charcoal, urban population increase is always a possibility [37]. Wood fuel is the main energy source in the majority of emerging African cities [38]. One of the fundamental materials used in the construction of both residential and non-residential buildings is forest wood. Buildings are becoming more and more necessary due to the increase in urban residents and money, particularly in emerging nations [39]. Forest wood products are preferred over other nonrenewable building materials like steel, aluminum, concrete, brick, and plastics due to their renewability. This is because using nonrenewable building materials would result in a huge rise in both the quantity of energy consumed globally and the amount the CO_2 added to the air. "Koch" [40] estimates that using non-renewable construction supplies is going to boost oil usage by around 717 million gallons a year and raise atmospheric carbon dioxide by nearly 7.5 million tonnes annually. Therefore, the yearly production of forestry timber needed to be greatly expanded to replace non-renewable construction materials. To better capitalize on the worth network over timber and associated goods, small-scale agricultural producers should be permitted to invest in the growth of local jungle enterprises. Forest market institutions ought to provide economic support to these producers to boost the generation of wood in rural areas. Additionally, it's critical to remove needless barriers, promote an equitable and open market, and involve farmer organizations in the formulation and discussion of forest policy to ensure that the regulations are acceptable for local farmers to participate in markets. To create a viable market for forest wood, wood suppliers should also enhance their institutions, improve their market strategies, and form strategic commercial alliances.

4.2 Regulating the Provision of Services

Regulation offers rewards from ecological services including reproducing crops and managing floods along with diseases, maintaining climates and adverse weather, and maintaining the standards of the soil and the air. Because they are normally imperceptible, these frequently are taken for granted. When people get hurt, they may suffer significant losses that are challenging to recuperate. The regulatory functions given to environments are among many important components for the long-term utilization of financial assets. The Assessment of the Millennium Ecosystem lists control as one of the ecosystems' potentially most important services [41]. Environmental regulations improve the reliability of provision by maintaining system capacity and enabling ecosystems to endure an abundance of circumstances, including challenges, which are often brought on by human activities. Therefore, it is important to make sure that managing ecosystem benefits serves a broad public interest on a "local, national, regional", and worldwide scale. Environmental amenities that control biodiversity are essential for urban environments. The need for environmental amenities in cities is growing, and it is predicted that this requirement will increase dramatically when city residents' double by 2050 [42]. One of the primary difficulties in delivering ecosystem services is the quick growth of metropolitan areas. The majority of the time, ecosystem services in urban settings are experiencing a steady reduction [43]. This is partially due to the disappearance of urban green spaces after construction projects. Urban areas are important in determining how people and nature interact, despite their substantial environmental impact [42]. Consequently, metro regions' capacity to deliver ecological benefits is compromised, resulting in an increased dependence on the ecosystem services offered by rural areas. To meet the requirements and preferences of its residents, cities depend on the ecosystem services provided by their rural areas, according to the research by "Larondelle et al." [44] into the regulation of ecological amenities in 300 towns in Europe. The ecosystems' regulatory functions are extremely condition-dependent. There are notable regional differences in the state as well as patterns and change causes along with impacts, administration, and skill gaps, according to Smith et al. [45]. Therefore, each service is explained separately.

4.2.1 Regulating Air Quality and Climate

The last century's rapid economic and industrial expansion has resulted in a significant rise in "greenhouse gas emissions". As a result, quality of the air has become a significant global environmental issue. Among the most prevalent kinds of air pollution in cities are particulate matter, "carbon dioxide, nitrogen dioxide, ozone, sulfur dioxide, and sulfur dioxide" [46]. As a result, one of the primary causes of global warming is attributed to urban activity [47]. Ecosystem regulation offers climate-management goods and services to mitigate the adverse consequences of global warming on people's health and the welfare of other living creatures. Ecosystems regulate the climate in urban areas by utilizing jungles and open spaces that prevail in urban and rural locations. However, country trees do contribute significantly to the control of urban climate (Fig. 2).

4.2.2 Climate is Regulated Through Ecosystem Services

(i) Providing sources or sinks of greenhouse gasses, factors contributing to rising temperatures, and processes for cloud generation [48];
(ii) Improving evapotranspiration, which will improve cloud formation and precipitation [49]; and
(iii) Influencing the ability of the surface to absorb insolation, which in turn affects temperature and radiative forcing [50].

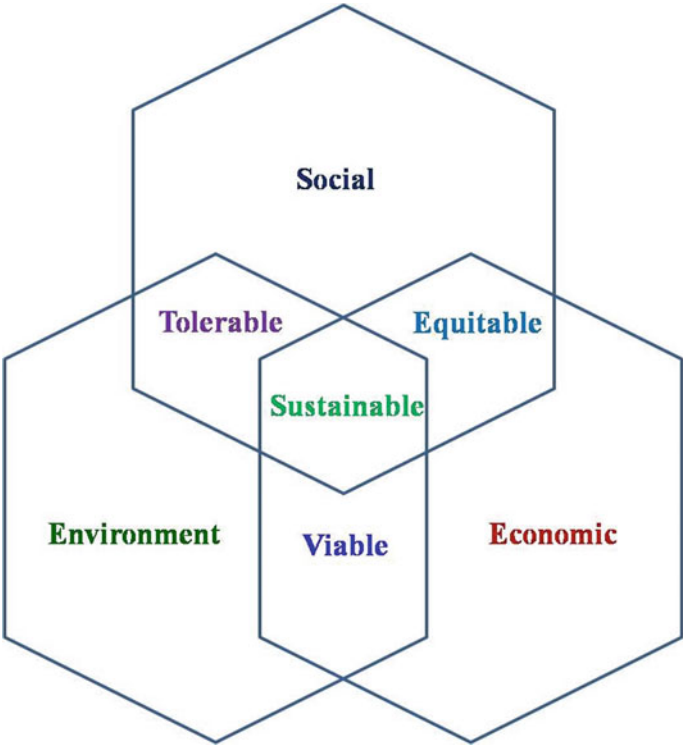

Fig. 2 Sustainable growth in rural and urban areas

Through the supply of shelter and shade as well as the control of humidity and temperature, ecosystems can also influence the local climate [48]. The health of people can be significantly impacted by microenvironment regulation, particularly in metropolitan settings. The systems that manage environments additionally manage the purity of air in cities. Forestry contributes an important role in regulating air purity by removing contaminants in the environment [51]. According to McPherson et al. [52], in 1991, trees in the Chicago region purified the air by removing an estimated 6145 tonnes of pollutants, at a cost of $9.2 million. Ecosystems provide essential amenities that allow individuals to adjust to changing weather patterns and global warming. This has led many charities and intergovernmental organizations to focus on creating ecological amenities-based initiatives for improved adaptations [53]. Relying upon ecosystem-related benefits was the most effective way to adapt to climate change because of its efficiency in reducing vulnerability, affordability, benefits over conserving biodiversity, and advantages for mitigating "climate change". Controlling heat waves in cities is one of urban ecosystems' other vital roles. When urban areas become warmer than the surrounding rural areas, an effect termed heat islands in cities occurs. Urban activities like traffic, industrialization, and building structures that absorb and re-radiate solar radiation are the main sources of heat that contribute to urban heat islands [54]. Rural areas with forest covers and green spaces offer an ecosystem service for reducing urban heat islands [55]. Therefore, increasing and maintaining ecological functions using jungles and open space is one strategy for minimizing regional climatic changes in urban environments. This has the dual benefit of delivering several ecosystem services and lowering climate extremes.

4.2.3 Storage and Absorption of Carbon

A process called capturing carbon involves conserving CO_2 or various kinds of greenhouse gasses to slow down global warming. As oxygen is released during photosynthesis and carbon is collected during the development of plant cells, carbon is sequestered during the growth phase of plants [56]. Twigs, leaves, and additional materials dropped on the jungle ground could hold the carbon until they rot or burn. Additionally, soils are very important in the storage of a lot of carbon. About 75% of the carbon on land is found in soils, which is three times more carbon than is found in living things [57]. Increased urban activity is rising atmospheric concentrations of greenhouse gasses like ozone, methane, and chlorofluorocarbons as well as carbon dioxide. These are the primary causes of global warming due to the atmospheric absorption of particular light wavelengths [58]. Urban areas have higher carbon dioxide emissions and a much smaller carbon sink than rural areas [59]. While several urban areas are performing well as carbon sinks, lots of metro areas sink much more carbon than they produce. At Pune Town, India, for example, 1 percent of all plant biomass is stored as carbon. Currently, the city's trees store 15,000 tonnes of carbon annually; this means that 99 percent of the city's emissions remain in the atmosphere and only two percent are absorbed by plants [56]. Rural communities can retain ecosystem benefits if there is equilibrium between absorption and output. The neighborhood, regional, and world temperatures are controlled by ecological functions through the storage and sequestration of excess greenhouse emissions through the environment. As they grow, the forms of trees alongside other plants efficiently fix atmospheric carbon dioxide. In rural areas, forests and other green spaces are crucial carbon sinks. According to estimates by Ugle et al. [60], planting four million trees in Canberra between 2008 and 2012 will save money on electricity, reduce pollution, and sequester carbon. All trees do not perform equally well as carbon sinks, claim Rathore and Jasrai [61]. Therefore, trees with high wood specific densities have a larger ability to store carbon than those with lower densities. Additionally, the vegetation should have a large canopy, develop swiftly, and produce biomass quickly, as per "Rathore and Jasrai" [61]. A plant that stores one-tonne carbon can remove "3.67 tonnes" of carbon from the atmosphere and discharge "2.67 tonnes" of oxygen into the atmosphere, according to Nowak and Crane [58]. When people realize how important trees are to this, their dedication to preserving and enhancing environmental services increases. The amount of "carbon dioxide" in the atmosphere in urban areas can be somewhat balanced by the forest in a maintained effectively rural location. Furthermore, they may have a significant effect on the population health and environmental quality of the metropolitan areas.

4.2.4 Extreme Occurrences Are Moderated

Floods, hurricanes, tsunamis, landslides, and extremely hot weather conditions are examples of extreme weather conditions or natural hazards. The consequences are higher when these deadly events occur in areas having an elevated population density, such as big cities. Urban regions are more vulnerable to extreme weather occurrences than rural areas are [55, 62]. One of the harmful natural hazards that many metropolitan places across the world must contend with is flooding. The form of flooding flow, the covering from large parts of the ground with roadways, structures, and pavement, blocking pathways, to constructing draining are the main factors that intensify the consequences of floods in urban environments [63]. The possibility of landslides is another extreme event that might occur by actions related to societal growth besides natural events. Dolidon et al. (2009) state that reducing the risk of land sliding requires careful management of ecological benefits including forests. Additionally, properly maintained woods lessen gully erosion and other landslide hazards [64]. Therefore, developing and managing forests are preferable approaches to respond to landslip threats. To reduce losses caused by severe climate and weather conditions, ecosystems absorb flood water, stabilize slopes, break rapid floods and storms, and provide cooling services. The increasing severity of "climate change-related" disasters, such as extreme rainfall and rising sea levels, is making this ecological function increasingly important on an international basis. Communities can be better protected by including ecosystem services in efforts to reduce natural hazards [65]. The services that forests offer to prevent hazards are valued. According to studies by Dolidon et al. [64] and Sakals et al. [66], the benefits of forests include a decrease in the risks of floods, landslides, snowfall, and rock falls. Forests should be actively managed to keep an elevated level of community protection. How much protection the forest provides depends on its condition and the kind of harm it presents. If the type of risk is recognized and forests are protected and maintained properly, the expected protective services can be accurately predicted [66].

4.2.5 Treatment of Wastewater

The biggest threat to the quality of both surface and subsurface water comes from urban activities, particularly industrial activity. These actions release some harmful substances into the water sources. In exchange, these poisonous substances eliminate significant aquatic creatures, rendering the water unsafe for eating by both people and animals. Wetland application has emerged as the ideal answer following years of research into the most effective, cost-effective way to remove pollutants from water [67, 68]. Ecosystems like wetlands operate as natural environmental neutralizers by filtering and decomposing wastewater that has been contaminated by human activity. Soil bacteria naturally eliminate dangerous materials and most contaminated water is cleansed. The necessary effect that wetlands in their natural state serve in processing enormous amounts of wastewater is currently the fundamental argument in favor of wetland preservation and upkeep [67]. In poor countries, wetlands, artificial or not, offer the finest solution for treating sewage from cities. Additionally, there is a lot of opportunity for the usage of both naturally occurring and artificial wetlands in growing metropolitan areas. Wetland utilization is generally minimal in affluent countries due to the need for the best and most expensive wastewater treatment methods [69]. The majority of the time, urban wastewater is released into rural rivers and open spaces, where it then flows onto agricultural fields. Wetlands are essential in this case because they help to mitigate the possible consequences of these poisons. However, it can be difficult to provide easy and affordable wastewater treatment in rural locations, especially in developing nations [70]. Because of this, the relationship between rural and urban regions is essential, and urban areas need to help create, protect, and preserve wetland environments within.

4.2.6 Maintaining Soil Nutrients and Preventing Erosion

Soil is the basic building block of the nutrient chain. A good yield of nutritious food is produced by fertile, healthy soil. Urban food production depends heavily on the fertility and nutrient content of the soil. Plant growth depends on nutrients in the soil. According to Bot and Benites [71], soil receives nutrients from both minerals and organic matter that result from the breakdown of living things. For agricultural production, plant development, and the proper operation of ecosystem services, fertile soil is a must. Agriculture is able to feed the rapidly expanding urban population because of fertile and well-managed soil. One of the three needs indicated for boosting per capita agricultural productivity is improving soil fertility and replenishing depleted soil [72]. Soil erosion is a major contributor to the processes of increasing desertification, degradation of the soil, and fertility loss. These processes all lower crop production and food availability. Erosion of soil continues to undermine the foundation of resources for agriculture in a variety of regions across the globe. The primary biophysical cause of small-scale farmers' decreased per capita food output is the degradation of soil fertility on agricultural grounds. Regardless of all corrective measures, the amount of food produced per person in Africa will continue to decline if soil erosion is not successfully addressed [72]. By halting soil erosion, ecosystem services like forest cover offer an essential regulatory function. Through natural mechanisms like stopping floods and holding soil from eroding, forests ensure soil fertility and prevent soil erosion. Controlling stand density contributes to good forest management, which is essential for avoiding and minimizing the erosion of soil, according to the research by "Razafindrabe et al." [73]. In the absence of trees, loss of soil could occur, turning the land into water. Furthermore, as the area loses its rich soil, which fuels the cycle of soil erosion, farmers will keep felling more trees. It's important to understand these effects. The removal of forest cover could result in the loss of many thousand acres of farmland [74]. Furthermore, the soil determination becomes more susceptible to the elements—rain as well as wind—when additional wood is removed. For instance, maintaining forests within regions of drought is crucial to halting soil loss. Forests must be managed sustainably if soil erosion is to be prevented and soil fertility is to be preserved. Slopes are made more stable by forests, which also give the soil the support it needs to resist erosion. Comprehensive forest management techniques will also assist in controlling and reducing the risk of soil erosion, such as by taking steps to keep forest cover in places that are vulnerable to it [74]. By making investments in their management and conservation, forests can serve as an essential safeguard for soil resources. Thus food safety and the health of the environment can be maintained when vegetation and forests are administered carefully and protected against careless cutting. Soil erosion will be lessened as a result, and agricultural production will be increased to its highest level. To satisfy their basic requirements and maintain a healthy way of life, urban regions must thereby give priority to the environmental amenities that rural regions supply.

4.3 Cultural Offerings

Cultural facilities constitute the other major ecological function and are mainly present in rural regions. Cultural environmental services are the physical benefits that we derive from the environment. These benefits include spiritual fulfillment, environmentally friendly tourism, pleasure, and beautiful aspects. There are significant connections between cultural resources and other environmental programs. In forests, for example, the goals are not only service provision or regulation but also ecotourism and recreation. Psychological relaxation constitutes one of the many social services offered in rural locations. According to WHO [75], depression is the biggest driver of disabilities globally and considerably raises the total global burden of disease. The countryside is a fantastic place to walk and unwind when suffering from psychological disorder. It is evident how important rural areas are for maintaining people's physical and emotional well-being, despite the fact that this effect is difficult to measure. In comparison to their rural equivalents, urban regions offer substantially fewer natural recreational services [76]. This suggests that there are fewer opportunities for depression recovery and lower levels of mental well-being in urban locations. Because of this, many visitors from all over the world like rural destinations since they provide people with pleasurable opportunities to engage with the natural world, historical heritage, and cultural traditions [77, 78]. For this reason, a lot of people who live in cities depend on farms for leisure. Consequently, having an association with rural regions is essential. The other significant and expanding ecosystem function provided by rural regions is ecotourism. Mostly for educational and research purposes, it is a tour of unexplored, unaltered rural places. Ecosystems, in particular biodiversity, are crucial to the growth of the ecotourism industry. For many nations, this can lead to significant economic advantages. Academicians' expertise is significantly increased through ecotourism, which also provides rural residents with work opportunities. Additionally, it is crucial for the recovery of damaged lands and the preservation of biodiversity and ecologically sensitive places [79]. More than others, metropolitan-based educational institutions as well as research organizations require these services. This is primarily because rural areas have so many distinctive ecosystems and cultural landmarks [80]. Therefore, by establishing strong links between these educational organizations as well as environmental tourism sites, great thought should be given to the preservation of these ecotourism sites. Aesthetic appreciation, motivation for art and culture, and spiritual experiences are among other essential elements of services associated with cultural environments. People have always been inspired by and connected to the environment in general, and by ecological diversity as well as landscapes that are natural in particular. Furthermore, in many cultures around the world, certain natural settings, like monasteries, are revered or have religious significance. The sustainable exploitation of natural resource services is seriously threatened by urbanization. It is the primary cause of the decline in biodiversity in urbanizing environments [81]. It is anticipated that the rapid urbanization occurring globally will lead to a considerable decline in biodiversity, the extinction of endemic species, the deterioration of ecosystems, modifications to land utilization, and an obstacle to the spread of species across several locations [81]. Therefore, preserving and repairing the natural environment would be the best preventative measure against the negative effects that urbanization has on the functions provided by the cultural ecosystem. Furthermore, zoning for land uses that restrict urban growth in environmentally vulnerable regions will help ensure that both the general city residents and rural regions receive sustaining benefits from ecosystems.

4.4 Supporting Services

Examples of supporting services provided by ecology include providing, controlling, and social elements like the nutritional cycle that keeps Earth's living species healthy. Services that facilitate the additional resources' performance are known as complementary ecosystem-level services. In contrast to offering, controlling, and supplying cultural amenities, sustaining ecological functions helps individuals indirectly or gradually over time. In terms of the financial worth of these amenities, farmers and rural communities stand to gain much by sustaining ecological benefits in terms of both their surroundings and the economy. The participation of these auxiliary environmental amenities has additional indirect benefits for city residents. In order to improve rural–urban links, these ecological services should be preserved. Main production, living thing preservation, and nutrient cycling are a few of the essential roles that ecosystem services play. Because they support the provision and maintenance of each of the additional environmental benefits that are primarily found in rural regions, such amenities are essential to maintaining the "rural–urban" link. One of the most important ecological processes is the cycling of nutrients. The recycling of resources by the environment, such as "oxygen, carbon", phosphorus, "calcium, nitrogen, etc.", is explained by the nutrient cycle. Reusing certain essential elements is essential to the survival of life on Earth and ensures that it will always exist. The food chain cycle, according to Bailey [82], is made up of non-living and living parts that can be created by "geological, biological, and chemical activities". For this reason, nutritional cycles are also known as “biogeochemical cycles”. The maintenance of genetics and biodiversity is an additional essential to sustaining ecological function. Biological or genome diversity is the term used to describe the genetic variation found in populations of a species. Every species possesses an individual trait that affects its ability to adapt. Because of this, local genetic species are a foundation for the development of other species and are locally well-adapted. The sustainability of the ecosystem as a whole and the long-term viability of species depend on genetic diversity. The growing urbanization and unrestricted land use changes in Africa are the main causes of the genetic biodiversity being put under increasing pressure [83]. The other crucial ecosystem services, which essentially support the other ecosystem services, are habitat formation and primary production. The foundation of this service is the development of environments that offer all the necessities for a living entity to exist and operate, including energy. Different habitats are offered by each ecosystem, and these habitats might be crucial to the life cycle of a species. Primary production in the environment is a procedure by which novel vegetative tissue is created through photosynthesis, according to Field et al. [84]. Main production finally results in the emergence of a new plant in the environment. Whether directly or indirectly, primary producers are where consumers, including humans, get their energy. Primary production is a source of food for almost all living things. In ecosystems where humans are dominant, such as metropolitan regions, species losses are speeding up. Furthermore, there has been an acceleration of the speed of depletion of the earth’s resources, and as diversity decreases, the potential for restoration is decreasing rapidly [85]. However, these trends have a strong chance of being reversed, and repairing the environment is crucial to raising output. For example, production has increased in marine ecosystems beyond the value of two due to the regaining of ecological diversity [85]. In general, all regulating services (like controlling the climate, preventing erosion, treating wastewater, etc.) and provisioning services (like providing “water, food, resources, forests, etc.”) mostly depend on the supporting ecological services. If the supply of basic services is not protected, there will be no life on the planet, particularly in urban regions. Cities should be cautious while preserving these services, and they should foster the connection between urban and rural regions by supporting their conservation, as most of those facilities are located in rural areas. One of the main challenges to maintaining the fundamental ecological functions may be the modern agricultural practices being employed. Understanding the biological functions as well as ecological implications of farming enhancement is essential in this scenario to regulate to enhance agricultural expansion methods, protect natural resources, and ensure the production of food for more people. Present demand; “mechanized, high-input” farming practices are proven to have an influence on the capacity to support ecosystem services [86]. Over time, this might make it more difficult for them to provide the regulating and ecological functions needed by the growing number of people living in cities.

5 Conclusions

“Rural-urban” linkages are essential for advancing national development because they facilitate the movement of “people, information, technology, goods, and services” between urban and rural regions. The economic, cultural, as well as social growth of both urban and rural populations depends on their interconnection. The economic, cultural, as well as social growth of both urban and rural populations depends on their interconnection. If rural communities are geographically, socially, and environmentally isolated, urban development is typically impossible. It is almost always possible to have city growth lacking links to rural areas. While connectivity between cities and rural regions is crucial, metropolitan areas require more attention than other areas. Almost everything needed for healthy urban living comes from rural regions, including “raw materials, clean air, food, water, and firewood”. Therefore, when planning for national development generally and urban growth specifically, rural development should be the top priority. But it’s important to remember how urbanization benefits rural places as well. It is important to keep in mind that the effect of city economies on rural regions will be less severe if the environmental benefits provided by rural regions are robust. The cities will be vital to rural towns once the farming or rural industry is expanding. Here, we have advantages for both parties because rural regions provide food, timber, raw materials, and other necessities to urban areas, while urban areas provide marketplaces, consumer goods, agriculture inputs, and other resources to rural areas. As a result, rural development is necessary before urban growth. This essay focuses on supplying, controlling, assisting, and sociocultural ecological services—the four basic ecosystem amenities. Rural areas serve as the fundamental building blocks of various ecosystem services. The majority of the resources in rural areas come as free gifts from nature and require little human work. To maintain their present and future uses, they must be handled with care. The ecosystem is where life on Earth originates. The biosphere wouldn’t exist at all without these ecosystem functions. More importantly, if equality is not ensured and future “national development” is not socially equitable; the growth of cities’ prices of agricultural assets may result in severe future shortages of basic requirements of life for urban residents. Therefore, the focus of policy ought to be on enhancing the capacity of rural ecosystems to provide services that are beneficial to people in urban areas as well. Investments in the maintenance and restoration of the ecological benefits that rural areas provide are likewise necessary for cities as well. The current trend of urban growth poses a threat to the ecological services that rural regions provide. Because numerous ecological services occur in rural locations, the functions offered by ecological systems are being limited by the external growth of metropolitan districts into these places. The rapidly expanding urban population will undoubtedly experience serious shortages of essential ecosystem services if these trends continue to invade rural areas. The life of the rural populace will likewise be impacted by these issues. Based on the notion that urban growth cannot have any bearing whatsoever on the supply of rural environmental benefits and village lifestyle, this calls for meticulously controlled "rural-urban" linkages. Because of the natural resources that rural regions provide, the population living there should also be given legislative consideration. Consequently, expanding the soft and hard facilities to link cities to rural regions, organizing sectors for crop products, generating job opportunities in city regions, setting up training programs for enhancing farming operations, and safeguarding environment facilities are among the demands that administrators must consider for powerful "rural-urban linkages".

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Impact of Emerging Contaminant on Farmland Soil

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Abstract The global focus on emerging contaminants is justified because of their harmful impact on human health and the urgent need to establish regulatory standards. The quantification of certain emerging contaminants in worldwide soil is measured in metric tons; however, Identifying the source of these contaminants in soil environments is difficult because of the diverse nature of the medium and the complex mechanisms involved in their interactions. Most emerging contaminants demonstrate a heightened affinity for solid matrices and tend to adhere to them. These emerging contaminants not only disrupt the functionality of soil but also impact plants and animals. The toxicity of these contaminants can be observed in cell cultures and animals within a range spanning from nmol to mmol. These substances tend to accumulate in root-based food crops, posing a potential threat to human health. The lack of a thorough understanding regarding the fate of certain emerging contaminants in anaerobic environments and their pathways within the food web hinders the development of effective bioremediation strategies, the restoration of polluted soils, and the support for global regulatory initiatives. Despite the established harmful effects of these contaminants on living organisms, there are currently no specific environmental laws or guidelines in place to address them. Additionally, available information concerning the impact of soil pollution from emerging contaminants on human health remains incomplete. Therefore, we present a comprehensive explanation of several notably significant emerging contaminants, specifically: PFAS, micro/nanoplastics, additives (biphenyls, phthalates), flame retardants, and nanoparticles.

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Our focus centers on quantifying the burden of contaminants in soil and examining the resultant repercussions.

Keywords Emerging contaminants · Soil · Chemical · Nanoplastics · Polybrominated diphenyl ethers

1 Introduction

Due to the swift progress in industry and agriculture, an increasing number of environmental contaminants are continuously infiltrating and permeating our biosphere. Most prior studies have primarily focused on assessing the environmental consequences of individual pollutants [1, 2]. However, in soil environments, pollutants are more commonly found as chemical combinations rather than isolated substances [3]. Bliss [4], in his analysis of the combined impacts of two toxins, initially classified compound pollution into additive, synergistic, and antagonistic effects. The cumulative toxicity of most pollutants does not simply result from the sum of the effects of individual contaminants; instead, it often exhibits synergistic or antagonistic effects stemming from the presence of multiple pollutants [5]. The existence of combined pollution in soil signifies the coexistence of numerous pollutants.

Emerging pollutants (EPs) encompass synthetic or naturally occurring substances that typically escape routine environmental monitoring but possess the capacity to enter ecosystems and lead to identified or suspected adverse impacts on both ecological and human health. The phrase “Emerging contaminants (ECs)” was introduced by experts in water quality management to label substances that are progressively identified in aquatic environments at minimal levels. These ECs find application in various sectors, serving as pesticides, pharmaceuticals, personal care items, disinfectants, surfactants, household products, nanomaterials, and even illicit drugs. Recently, there has been a growing global concern surrounding the environmental destiny of emerging contaminants (ECs) like perfluoroalkyl and polyfluoroalkyl substances (PFAS), microplastics (MPs), nanoplastics (NPs), additives such as biphenyl/phthalates, flame retardants like polybrominated biphenyl diethers (PBDEs) and organophosphorus flame retardants (OPFRs), and nanoparticles [7]. The term ‘ECs’ encompasses both newly developed compounds and chemicals that are progressively being introduced into the surrounding environments. Often, PFAS, MPs/NPs, FRs, PCBs, and nanoparticles have subsequent adverse effects on food safety and the well-being of ecosystems and human health [8]. Despite presenting substantial risks to a wide array of life forms, these contaminants fall outside the scope of existing environmental regulations. Unfortunately, the main origins of emerging contaminants in the environment include agricultural soils, urban runoff, and effluents from wastewater treatment facilities [9]. Numerous research studies have explored the movement of these contaminants within aquatic systems, including marine environments, surface waters, and wastewater [5, 9]. These studies originate from diverse regions worldwide, spanning Australia, Africa, Europe, Latin America, Asia, and

North America [9–12]. However, there has been comparatively less attention given to information regarding soil pollution caused by ECs [13, 14]. The worldwide burden of ECs in the soil is a matter of great concern, given that their concentrations can reach several hundred to thousands of milligrams per kilogram of soil. The lack of complete understanding regarding the fate and transformations of ECs in terrestrial environments has led to less stringent environmental regulations in many countries [15]. It is important to highlight that most emerging contaminants (ECs) persist in the soil even after being subjected to water washing for a week, primarily due to their stronger affinity for soil matrices compared to other pollutants [16]. Teijon and colleagues [17] conducted column miscible displacement experiments and observed that Naproxen, a nonsteroidal anti-inflammatory drug, exhibited limited sorption to aquifer matrices, indicating a stronger attraction to solid particles. Another noteworthy finding pertains to the complexation of ECs within soil matrices, a factor that can significantly influence their fate and toxicity in soil environments [11, 12]. Additionally, the adsorption characteristics of triclosan (TCS) to polyethylene (PE) were determined to have an adsorption rate of 29.3 mg per milligram per hour and an equilibrium capacity of 1248 mg per gram. In contrast, the adsorption rate values for TCS on polystyrene (PS) and soil particles were 0.27 and 0.60 mg per milligram per hour, respectively [13, 14]. Furthermore, substantial variations in the equilibrium capacities, measured in milligrams per gram, were evident in the pairings of triclosan (TCS) with polyethylene (PE) (1248), TCS with polystyrene (PS) (1033), and TCS with soil particles (961). Similarly, microplastics (MPs), including polyethylene (PE) and polypropylene (PP), exhibited similar trends. This demonstrated considerable variations in their interactions with polychlorinated biphenyls (PCBs). The documented levels (nanograms of PCBs per gram of MPs) fell within the range of 700, [18, 19]. These chemical phenomena contribute to the higher concentrations of specific emerging contaminants (ECs) in terrestrial systems compared to aquatic systems. For example, terrestrial and freshwater systems experience [20–22] higher levels of MPs than aquatic surroundings, and the widespread accumulation of microplastics (MPs) in both rural and urban soils can be attributed to human activities [6]. Understanding the interactions between soil environmental components and ECs, and determining whether these interactions lead to complexation, is of utmost importance. This complexation facilitates the bioaccumulation of ECs in terrestrial biotic components [23].

The primary route of exposure to emerging contaminants (ECs) for humans and other animals occurs when they consume plant-based foods contaminated with these substances. This is primarily due to the ease with which plants uptake and transport ECs from soils [6]. In food crops, emerging contaminants (ECs) typically exhibit the following pattern of accumulation: roots, shoots, fruits, and grains [14]. Moreover, ECs exert notable effects on plant functions. For instance, microplastics (MPs) have detrimental impacts on factors like germination rate, shoot height, and biomass, and can induce oxidative damage and genotoxicity in plants [24]. In vitro studies have revealed the non-target toxic effects of ECs on various model organisms or cells, including Dugesia japonica, freshwater mussels, bay mussels, raptors, the PA1-cell line, and the CYP1A-bla LS-180 cell line [25, 26]. These findings strongly underscore the potential health risks associated with ECs when they enter the human body. However, our comprehension of the full extent of the toxic effects of most ECs is still incomplete [27]. Despite the clear ecological hazards they pose, emerging contaminants (ECs) remain outside the purview of environmental regulations and policies. Recent reviews have concentrated on distinct ECs, encompassing diverse facets such as evaluating their presence in marine ecosystems, addressing contamination in aquatic environments, examining human exposure, studying plant absorption and distribution, understanding their role as endocrine disruptors, and investigating their behavior in wastewater systems [11, 28]. Nonetheless, there is currently no comprehensive source of concise information available in the literature regarding the toxicities and regulatory concerns associated with ECs of significant importance in soils [29]. Hence, the central objective of this chapter is to provide an insight into the environmental issues associated with significant emerging contaminants (ECs), including PFAS, microplastics (MPs), nanoparticles (NPs), additives like biphenyls/phthalates, flame retardants (PBDEs, new FRs, and OPFRs), and nanoparticles. It also delves into their potential impacts on health and emphasizes the importance of implementing comprehensive regulatory measures.

2 Major Emerging Contaminants and Their Sources

a. Per- and polyfluoroalkyl substances (PFAS) represent a category of chemical compounds utilized in the production of fluoropolymer coatings and products that exhibit resistance to high temperatures, oil, stains, grease, and water. Such coatings find application in a diverse range of products, including but not limited to food packaging material, fabrics that repel stains and water, non-stick products like Teflon, polishes, waxes, paints, cleaning agents, fire-fighting foams, industrial facilities involved in chrome plating, electronic goods, and oil recovery, landfill wastewater treatment plants, as well as living organisms such as fish, animals, and humans due to their propensity to accumulate and persist over time. The molecular structure of PFAS entails a chain consisting of interconnected carbon and fluorine atoms. Owing to the exceptional strength of the carbon–fluorine bond, these chemicals exhibit resistance to degradation in the environment. The primary route of human exposure to PFAS primarily occurs when individuals consume water or food contaminated with PFAS, usage of products containing PFAS, or inhalation of air containing PFAS particles. Given the slow rate of degradation, if any, individuals and animals are repeatedly subjected to these compounds, leading to the accumulation of certain PFAS molecules in the bloodstream over time. A report published by the Centers for Disease Control and Prevention, employing data from the National Health and Nutrition Examination Survey (NHANES), revealed the presence of PFAS in the blood of 97% of the American population [30]. Another NHANES report suggested a decline in blood levels of PFOS and PFOA among individuals since the removal of these chemicals from consumer products in the early 2000s. Nonetheless, the emergence of novel PFAS compounds poses challenges in terms of assessing exposure to these substances. The National Institute of Environmental Health Sciences (NIEHS) is responsible for conducting or funding research endeavors aimed at comprehending the intricacies of PFAS exposure and any subsequent health implications [31].

b. Micro-/nano-plastics. The term microplastics denotes fragments of plastic that possess a diameter smaller than 0.5 mm, which is approximately analogous to the size of a grain of rice. On the other hand, nanoplastics are considerably smaller, measuring at merely 100 nm or less. To obtain a more thorough grasp of the practical consequences of these measurements, it may prove advantageous to be aware that one nanometer equates to 0.000001 mm, and that a strand of human hair generally has a diameter of around 2.5 nm. Consequently, a nanoplastic exhibits a size that is at most 40 times the diameter of a strand of human hair. Primary microplastics are minute particles that are purposefully manufactured for commercial utilization, such as those found in cosmetics, as well as the microfibers that are shed from garments and other textile products, including fishing nets. Secondary microplastics are particles that form when larger plastic items, like water bottles, degrade [32]. In addition to their size, plastic properties can change due to weathering, involving alterations in the microtopography of the plastic. For example, previously smooth areas can become rougher, and the development of cracks, protrusions, and cavities can occur. It results in the transformation into irregular particles that possess an increased contact area [33]. These characteristics, combined with their hydrophobic nature, create a non-polar surface to which various pollutants like heavy metals, pesticides, polyaromatic hydrocarbons, antibiotics, fertilizers, and microorganisms can attach. This can result in potential harm to living organisms upon absorption [34, 35].

c. Plastic additives, referred to as substances incorporated during the manufacturing process, play a crucial role in enhancing the performance of the material when it is molded and utilized. Furthermore, plastic additives can be effectively employed to alter the polymer's characteristics and attain specific functionalities for distinct purposes, such as phthalates and biphenyls. Phthalates, commonly known as plasticizers, are a group of chemicals utilized to enhance the durability of plastics and aid in the dissolution of other materials. These compounds can be found in a wide array of products, ranging from vinyl flooring and lubricating oils to personal care items such as hair sprays, shampoos, and soaps [36]. On the other hand, biphenyl is an organic compound that exists in the form of colorless crystals. Chemical compounds containing a functional group consisting of biphenyl minus one hydrogen atom may adopt the prefixes xenyl or diphenylyl. Additionally, biphenyl possesses a distinctly pleasant odor. Its main uses involve the manufacturing of heat-transfer fluids, functioning as an intermediary in the production of polychlorinated biphenyls, and serving as a carrier for textile dyeing. Additionally, biphenyl has smaller roles in inhibiting mold growth in citrus fruit packaging, contributing to the production of plastics, optical brighteners, and hydraulic fluids [37, 38].

d. Polybrominated diphenyl ethers (PBDEs), Polybrominated diphenyl ethers (PBDEs), and polybrominated biphenyls (PBBs) pertain to a category of substances incorporated into specific manufactured goods to minimize the likelihood of fire occurrence. End products that may contain PBDEs include furniture foam padding, wire insulation, rugs, draperies, upholstery, and plastic cabinets for televisions, personal computers, and small appliances. PBBs were used in the past, and one form, BB-153, has not been produced in the United States since the 1970s. The manufacturing of these substances can result in their emission into the air, water, and soil. Furthermore, they can escape from products containing them or be released during the degradation of such products. These substances have low solubility in water; instead, they tend to attach to particles and settle at the bottom of rivers or lakes. Specific PBDEs can accumulate in certain fish and mammals when they consume contaminated food or water [39]. People may encounter PBDEs and PBBs through the consumption of contaminated food, especially items with a high-fat content like fatty fish. Another potential source of exposure can occur through inhalation of polluted air or ingestion of contaminated dust. Occupations that involve the manufacturing of these chemicals, as well as the production, repair, or recycling of products containing these chemicals as flame retardants, can also lead to exposure [40].
e. Organophosphorus flame retardants (OPFRs) have been identified in various environmental contexts and are acknowledged as emerging contaminants. Given the adverse effects associated with OPFRs, numerous researchers have directed their efforts toward examining the absorption, bioaccumulation, metabolism, and internal exposure processes of these compounds in both animals and humans [41]. OPFRs are extensively used in industries like furniture, textiles, construction materials, electronics, and various processing chemicals, making them one of the most employed flame retardants. Additionally, OPFRs are frequently used as plasticizers in products like floor polishes, coatings, engineering thermoplastics, and epoxy resins [42]. OPFRs exhibit a broad spectrum of physical and physiological attributes in the environment, such as solubility, logKow value, vapor pressure (VP), and bioconcentration factor (BCF), which are specific to them. These characteristics play a crucial role in assessing the behavior of OPFRs in the environment and their impact on organisms [43]. Volatile OPFRs, including substances like tributylphosphate (TBP), triethylphosphate (TEP), and tri(2-chloroethyl) phosphate (TCEP), which have higher vapor pressures, are more prone to release into the atmosphere and subsequent deposition on dust when compared to larger or heavier OPFRs [44]. Conversely, OPFRs with greater molecular weights, whether aryl or alkyl, exhibit increased hydrophobicity and similar bioconcentration factors (BCFs), resulting in a stronger attraction to sediments and soils. Additionally, chlorinated OPFRs have displayed enhanced water solubility and continue to pose a risk to aquatic organisms.
f. Nanoparticles, which are minute particles measuring between 1 to 100 nm in size, possess distinct physical and chemical properties that differ from their larger counterparts, rendering them imperceptible to the human eye. Currently, nanoparticles are employed in the manufacture of products like scratch-resistant

eyeglasses, crack-resistant paints, anti-graffiti coatings for walls, transparent sunscreens, stain-repellent fabrics, self-cleaning windows, and ceramic coatings for solar cells [45]. Nanoparticles can be classified into two categories: rigid types, such as titania (titanium dioxide), silica (silica dioxide) particles, and fullerenes, and flexible ones, like liposomes, vesicles, and nanodroplets. Naturally occurring nanoparticles (NNPs) are commonly distributed in various realms of the Earth, including the atmosphere, hydrosphere, lithosphere, and even the biosphere, independent of human activities [46].

3 Contamination of Farmland Soil with Ecs: From Sink to Source

The importance of soils cannot be overstated as they serve as a vital global natural resource, providing essential services to all forms of life and acting as the basis for human civilizations. They have a significant impact on the circulation of both natural elements and artificial substances, whether they are intentionally introduced for diverse objectives or deposited from the atmosphere and aquatic settings. At present, global societies are placing substantial pressure on the Earth's ability to support life due to the excessive production and utilization of synthetic chemicals [6]. Farmland Soils, which include lands classified as prime, unique, or of statewide or local significance based on their soil type as defined by the Code of Federal Regulations, CFR title 7, part 657, are specifically suited to produce food, feed, fiber, forage, and oilseed crops, and are therefore available for such purposes. Farmland soils can be used to identify and assess the extent of lands with productive soils that may be eligible for protection under the Federal Farm and Ranch Lands Protection Program (FRPP). This program, authorized by the Farm Security and Rural Investment Act of 2002 (Farm Bill), aims to prevent the conversion of working agricultural land to nonagricultural uses, aligning with the Connecticut Department of Agriculture's Farmland Preservation Program's goal of securing a land resource base for future agriculture in Connecticut. The pollution and environmental deterioration attributed to synthetic chemicals, arising from both living and non-living elements, pose a formidable obstacle in ensuring access to clean water for more than 900 million people, as well as numerous animals and plants [47]. The pollution of soils via manmade chemicals is increasingly becoming a significant issue for society. This issue is exacerbated by the existence of industrial facilities, which frequently contribute to accidents, inadequate waste management practices, and excessive production and use without considering the necessity for environmental regulations. Moreover, the deposition of pollutants from atmospheric emissions and their subsequent transportation can widely disperse contaminants in soil environments, transforming them into important repositories for these harmful substances. The concept that "pollutants do not recognize borders" has become increasingly apparent thanks to the development of precise analytical tools and high-resolution techniques, which aid in the detection and measurement of contaminants in various mediums, including soil.

The transfer of mass, energy, and genetic data, along with their transformations, establishes permeable soils as the primary interface connecting the Earth's critical zone, which includes the atmosphere, vegetation, and geosphere [6, 48]. Several soil characteristics, including pH, redox conditions, temperature, moisture levels, organic carbon content, and clay content, play a role in the adsorption and desorption of emerging contaminants (ECs). However, microbial activity primarily governs the destiny and transformation of ECs [49, 50]. The organic matter within the soil contains sites that facilitate the diffusion and sequestration of organic contaminants in rubbery and glassy phases. The resistance of certain contaminants to degradation through biological, chemical, and photolytic processes is influenced by their hydrophobic and lipophilic attributes, as well as their chemically resistant structure. Additionally, factors like pH, electrical conductivity, soil type, and prior exposure to soil matrices significantly impact the persistence of ECs [51]. While the behavior of these contaminants in aerobic soil conditions has been thoroughly researched, our understanding of their fate in anaerobic conditions remains limited [52, 53]. Understanding the fate of ECs in anaerobic environments is crucial for the development of effective strategies to remediate contaminated soils. Flooding conditions lead to soil becoming anaerobic, making it essential to gather critical information on the fate of ECs in anaerobic environments for soil ecosystems. These conditions significantly influence the routes by which emerging contaminants (ECs) are conveyed. Climate change events, including soil warming, can have adverse impacts on the transport routes of pollutants. Research conducted by Yang and colleagues [49] and Str°a°at and others [55] has shown that soil warming can amplify the movement and transformation of contaminants within soils. The dramatic shifts in precipitation patterns induced by climate change can also alter the mobilization, movement, and cycling of pollutants within the soil. Increased surface runoff and erosion resulting from intensified rainfall or storms further contribute to the conveyance of contaminants from the soil. Agricultural activities such as plowing and irrigation can expedite the release of soil particle-bound contaminants, which can subsequently be taken up by plants [56]. Consequently, contaminated soils can serve as not only a source for the transport of contaminants to other media but also as a site for their transformation, potentially facilitating trophic transfers. Plants possess the ability to absorb pollutants from the environment. For instance, it has been estimated that in 2002. In the central area of Beijing, China, trees were responsible for the removal of approximately 1261 tons of pollutants from the air [56]. Comparable findings suggest that greenbelt vegetation can enhance air quality in the vicinity of walkways by 7–15% [58]. In Strasbourg, France, trees effectively eliminated 88 tons of total atmospheric pollutants, encompassing 12 tons of PM10 and 5 tons of PM2.5 [59], and 7% of total air pollutants were trapped by vegetation in Marylebone and London [60]. These findings collectively demonstrate the strong interaction between plants and pollutants.

Accurately measuring soil contaminants is a daunting task because of the lack of well-defined chemical extraction methods and the complex interactions between contaminants and soil components. With the passage of time, the deposition of solid waste and materials originating from diverse human activities such as industry, mining, agriculture, livestock, military, and commerce can modify the chemical and biological attributes of soils, thereby resulting in the degradation of ecosystem services [61]. The Working Group of the International Union of Soil Sciences (IUSS) focused on Soils in Urban, Industrial, Traffic, Mining, and Military Areas emphasizes the critical role of urban soils, heavily impacted by human activities, in the sustainability and resilience of cities [62]. Environmental issues related to the presence of contaminants are more prominent in urban soils compared to rural soils. Nonetheless, both traditional and emerging contaminants present substantial scientific and societal challenges to global soil well-being. These challenges transcend apprehensions about soil health since they engender intricate and cascading ramifications on the well-being of individuals and the entire ecosystem. Since most of these contaminants eventually enter the soil environment via household and industrial waste, they collectively contribute to the overall global soil pollution.

After the introduction of a contaminant into the soil, its subsequent fate is contingent on a multitude of factors. Among these factors, the type of soil stands out as one of the most influential determinants. Soil chemical composition can affect the effectiveness of the removal of compounds. Notably, volcanic soil performs better than sandy soil in efficiently removing carbamazepine [63]. Another important factor is temperature, as the concentration of ECs tends to be higher during cooler months compared to the hottest months [64]. In the natural environment, specific chemicals can undergo diverse processes, including volatilization and photodegradation, while others may be carried through soil runoff or erosion into surface water. Some chemicals possess the capacity to infiltrate groundwater and/or adhere to or detach from the solid and colloidal constituents of organic and inorganic soil. Moreover, certain compounds can undergo partial or complete chemical breakdown and/or biodegradation [65]. In some instances, they may also be taken up by plants, with the roots accumulating the emerging contaminants. The chemical properties of the contaminants also assume importance, with lipophilicity, or the ability to be absorbed by lipids, standing out as one of the most crucial factors [66]. Environmental conditions hold the potential to influence the chemical pathways involved in the metabolism of emerging contaminants (ECs) within the soil. Notably, the soil environment undergoes frequent shifts between aerobic and anaerobic conditions. As such, electron-accepting processes (TEAPs) are a critical aspect to take into account. TEAPs represent the final step in the overall breakdown of organic material and the microbial respiration process [67]. In a recent investigation, the examination of TEAPs in soil unveiled that certain chemicals could be degraded under aerobic conditions, whereas others necessitated sulfate-reducing conditions, which correspond to the anaerobic state. Compounds such as carbamazepine, present challenges in terms of degradation under natural conditions [68]. The capacity of the soil to adsorb and allow the passage of emerging contaminants (ECs) plays a substantial role in determining their fate. An experiment conducted using soil composition columns illustrated those soils with minimal clay content experience more extensive migration of ECs. Certain pharmaceutical compounds, such as carbamazepine and hydrochlorothiazide, exhibit lower mobility, with their behavior remaining unaffected by the pH of the soil. In the experiment mentioned earlier, the majority of compounds were detectable after a week of washing the soil columns, indicating their potential persistence and the possibility of contamination of groundwater [69]. In 2009, a comprehensive report on wastewater biosolids in Norway underscored the significance of soil density, infiltration, distribution coefficient, degradation rate, and plant absorption as essential factors in forecasting the stability and accessibility of emerging contaminants (ECs) in the soil. For instance, an elevation in soil density correlates with a reduction in the concentration of heavy metals. The degradation rate of each EC is directly influenced by temperature and is linked to its half-life. Moreover, precipitation can impact the infiltration of each pollutant into the soil [70]. As previously mentioned, the introduction of antibiotic-resistance genes into the soil is associated with the use of manure. In 2020, Radu and colleagues [71] conducted a study on the inherent resilience of agricultural soil to manure practices. The researchers assessed the presence of antibiotic resistance genes at three points: before the application of manure (considered as the baseline), during a crop-manuring campaign, and during a campaign where manure was not applied. The results revealed that the use of manure led to an increase in the relative abundance of antibiotic resistance genes. However, following the application of manure, the concentration of these genes returned to the baseline levels within a single crop-growing season. Furthermore, the application of pesticides resulted in an elevation in the relative abundance of specific genes (aph(3')-IIa, ermB, and tet(W)) in soil that had not received manure treatment. Identifying patterns of antibiotic resistance is feasible in sediment. In a research effort conducted in Costa Rica by Arias and colleagues [72], an escalation in antibiotic resistance within microbial communities was noted in cases of continuous exposure to antibiotics. The findings indicated that pristine environments like the Palo Verde National Forest maintained baseline antibiotic levels. The concentration of antibiotics was linked to various agricultural and farming practices. Microbial communities displayed lower resistance patterns in sediments from agricultural fields, and intermediate levels in aquaculture, and the highest levels were observed in sediments from swine farming [73].

4 Impact of Emerging Contaminants on Farmland Soil

Emerging contaminants like heavy metals, microplastics (including nanoplastics), and antibiotic-resistance genes have been widely identified in farmland soils and aquatic environments. This presents a potential threat to the growth of global crop plants and food safety. These contaminants exhibit characteristics such as long-range mobility, persistence in the environment over extended periods, accumulation in organisms, and toxicity to humans and other living beings. When evaluating the risk posed by pollutants in agricultural soils, it is crucial to acquire knowledge about how these substances behave in different abiotic and biotic soil compartments. Furthermore, understanding the mechanisms governing their reactivity, transfer, bioaccumulation, and, ultimately, their toxic and ecotoxicological effects at various levels of biological integration is essential [75 Hence, it is crucial to explore the noxious effects and the mechanisms governing the absorption, conveyance, accumulation, and alteration of emerging contaminants in crop plants, and to create biological soil remediation technologies. Earlier investigations have predominantly concentrated on the physiological, biochemical, and molecular toxicity of external pollutants and their mitigation approaches. Nevertheless, there is a scarcity of data regarding the toxic mechanisms of emerging contaminants in crop plants, as well as the innovation of new strategies for remediating agricultural soils [74, 75]. Soils polluted with Per- and polyfluoroalkyl substances (PFAS) have shown significant endocrine-disrupting activity, contributing to the restoration of the soil. PFAS may bring about alterations in soil characteristics and operations [76]. The accumulation of PFAS at lower concentrations has a significant influence on soil respiration, litter decomposition, and the abundance of soil bacteria [77], and it also influences water availability within aggregates. The sorption tendencies of PFAS to soils with varying textures and organic carbon levels align with their hydrophobicity, following the same sequence [76]. For instance, PFBS, which exhibits low sorption affinity to soil particles, is more prone to interact with soil microbes, thus having an impact [76]. Nonetheless, this impact is not solely linked to hydrophobicity, as greater hydrophobicity can lead to heightened bioaccumulation and subsequently increased toxicity to soil microorganisms [78]. This might elucidate the more pronounced influence of PFOS on specific processes regulated by soil microbes. At environmentally relevant concentrations, PFAS, especially the short-chain PFBS, exhibits a favorable effect on litter decomposition within the soil. This outcome implies that PFAS existing in soils could potentially influence ecosystem processes. The heightened decomposition could result in the release of carbon in the form of CH4 and dissolved organic carbon, consequently influencing carbon reservoirs in the soil.

The ecological ramifications of micro(nano)plastics (MNPs) demonstrate that these particles have the potential to influence the cycling of soil nutrients through their mediation of soil nutrient availability, soil enzyme activities, functional microbial communities, and the subsequent ecological functions associated with these factors. Moreover, the impacts of MNPs are subject to variation, which is contingent upon the characteristics of the MNPs themselves (i.e., polymeric type, size, dosage, and shape), the presence of chemical additives, the prevailing physicochemical conditions of the soil, and the composition of the soil's biota [80]. Given the intricate nature of the interactions between MNPs and soil, it is imperative that comprehensive experiments, encompassing multiple scales and employing environmentally relevant MNPs, are conducted to shed light on the consequences of MNPs on soil nutrients. Through gaining a deeper understanding of the influence exerted by MNPs on soil nutrient cycles, this chapter holds the potential to offer guidance for policy-makers and managers, to safeguard soil health and ensure the implementation of sustainable agricultural practices and land use strategies [81, 82]. Biodegradable plastics are regarded as an ecologically responsible substitute for conventional plastics within the agricultural sector. Nonetheless, the potential impact associated with biodegradable plastics, particularly concerning the release of organic additives, remains a significant cause for concern [83]. Residues from conventional plastic mulch can endure in farmland soil for extended periods, thus presenting long-term environmental risks. Even tiny fragments of plastic mulch that become integrated into the soil or undergo repeated fragmentation can potentially release a variety of organic additives, including plasticizers, stabilizers, and chain extenders, into agricultural soils. These plastic additives are essential for improving the performance of polymers, with plasticizers designed to soften PVC [84]. Common additives typically found in agricultural mulches include plasticizers, dyes, photo stabilizers, and prooxidants. Numerous studies have reported the presence of plastic additives in agricultural soil, notably plasticizers, antioxidants, and stabilizers. The harmful impacts of organic plastic additives on soil organisms have been extensively documented in the scientific community. Through a systematic paper selection process, toxicological data has been collected, highlighting that phthalate esters (PAEs), bisphenol A (BPA), and brominated flame retardants are the most hazardous plastic additives. These substances have been the focus of significant research due to their identification as potentially carcinogenic, mutagenic, endocrine-disrupting, or capable of bioaccumulation in the soil, thereby affecting both the composition and the biologically active elements of the soil [81].

5 Removal and Remediation Strategies of Emerging Contaminants

In the year 2012, a study was undertaken to identify the most efficacious approach to eliminate emerging contaminants (ECs) from biosolids obtained from wastewater treatment. The research determined that the most effective approach for organic matter stabilization involves composting, followed by thermal drying. Furthermore, it was determined that anaerobic treatment exceeds aerobic treatment in terms of EC removal (2012). The sorption constants for emerging contaminants (ECs) were relatively modest and showed variations depending on the physicochemical attributes of the contaminants and the soil. In aerobic conditions, ECs were susceptible to microbial degradation. Nonetheless, in anaerobic conditions, the endurance of ECs was lower in comparison to aerobic conditions. Sucralose and carbamazepine displayed the greatest resilience among the ECs. These two substances were proposed as potential markers for evaluating the effects of soil and groundwater contamination [83]. Presently, there are ongoing endeavors in the field of remediation strategies for contaminated soil. Among these strategies, electrochemical technologies exhibit significant promise due to their capacity to operate without the need for reagents and without generating secondary waste or sludge following treatment [85].

Electrokinetic remediation involves the application of a low-intensity direct current between two electrodes. This process initiates an electrolysis reaction at the inert electrodes, leading to the creation of protons (at the anode) and hydroxyl ions (at the cathode), thereby establishing a pH gradient [86, 87]. In research conducted in Portugal, this concept was applied to both soil and the irrigation water discharged from a rice field. Before the remediation process, the soil consistently maintained an electrical conductivity (EC) level of 20% to 100% for six days. Nevertheless, in vitro electrokinetic remediation exhibited a 30% enhancement in the elimination of ECs from the soil compared to natural attenuation, effectively averting their dispersion within the soil [86, 88]. These results provide validation for the effectiveness of electrokinetic remediation as a promising approach for extracting and containing the dispersion of emerging contaminants in the soil [86]. Another remediation method entails the use of the Fenton oxidation reaction, which has demonstrated its efficiency in water environments. The principle of this process involves the initiation of a chain reaction through the interaction of ferrous salt and H2O2 with the target pollutants. This reaction can take place in an acidic aqueous solution (pH around 3) or within a solid matrix comprising carbon materials, clay, polymers, or zeolite [87]. A thorough assessment of the Fenton reaction has showcased its reliability, reusability, sustainability, and adaptability in eliminating emerging contaminants like artificial sweeteners, flame retardants, PPCPs, and steroid estrogens from water and wastewater [87]. Nevertheless, further investigations are necessary to substantiate the effectiveness of this method and its real-world application [89].

Conventional strategies employed to address the issue of antibiotic removal have demonstrated limited efficacy [90]. Conversely, bioremediation presents a fresh perspective on the matter, relying on the natural breakdown and utilization of these compounds by microorganisms to eliminate antibiotics from the environment [91, 92]. A group of scientists, led by Yang and colleagues [93], recorded the decomposition of tetracyclines, β-lactams, and sulphamethoxazole antibiotics within sludge by employing bacterial strains, specifically Pseudomonas sp., Bacillus sp., and Clostridium sp. They determined that the efficacy of antibiotic biodegradation could be maintained across three degradation cycles using these isolated bacterial strains. Additionally, the study identified two distinct sets of potential microbial communities linked to anaerobic and aerobic degradation within the sludge, underscoring the presence of twenty-four antibiotic-degrading bacterial genera that played a significant role within the sludge [94].

6 Conclusions

Emerging contaminants ECs, commonly recognized as contemporary soil pollutants, have emerged as a matter of great concern due to their potential hazards to human health and the general well-being of ecosystem inhabitants. The presence of genotoxic and carcinogenic properties in most emerging contaminants (ECs) raises new concerns and underscores the importance of thoroughly assessing their soil accumulation, transmission routes, and the formulation of suitable policies and regulations. The worldwide accumulation of PFOA (1860 MT) and PFOS (>7000 MT) in soil has been steadily on the rise, resulting in their integration into terrestrial food chains and subsequent accumulation in food crops. Exposure to PFAS in soil accounts for 9% of human exposure, making it the third most significant source after exposure through food (40%) and water (30%). The examination of PFAS soil data exceeding 160 ng per kg of soil and the projected growth of the PFAS market suggest potentially severe consequences for both the environment and human health in the absence of regulations controlling the entry and movement of PFAS in soils. Given their high toxicity to animals and cells and their carcinogenic properties, PFAS presents substantial risks. Intensively cultivated lands have become hotspots for micro- and nanoplastics, with around 80% of plastic waste ending up in landfills, further exacerbating the burden on soil. The interplay between micro- and nano-plastics (MNPs) and heavy metals (HMs) within soil matrices engenders complex ECs, which generate even more pernicious compounds compared to MNPs in isolation. The worldwide manufacturing of phthalates and their swift migration from soil matrices to crop plants play a substantial role in human exposure. Phthalates disrupt the endocrine system and pose carcinogenic risks. Agricultural soils contain higher levels of PBDEs when compared to mountain and rural soils, and they also have a greater propensity for phytoaccumulation. This highlights the need for specific measures to regulate their movement through the soil. The primary routes of soil contamination by nanoparticles involve leaching from source materials in landfills and the utilization of biosolids. The unregulated influx of various pollutants into the soil matrix poses a threat to various forms of life. Nanoparticles have been demonstrated to manifest ecotoxic effects even at levels as low as 1 ppm, and their bioavailability remains inadequately understood. Metal-based nanoparticles, specifically, have been found to possess considerable endocrine disruption, cytotoxic, and genotoxic characteristics. Hence, these particles pose a substantial peril to human health.

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Soil and Soil Issues

Soil Formation, Soil Health and Soil Biodiversity

O. A. Adewara, T. C. Adebayo-Olajide, J. S. Ayedun, B. C. Kotun, A. J. Adeleke, A. David Brown, O. J. Alabi, and S. T. Ogunbanwo

Abstract Increase in human population has led to industrialization and deterioration of the environment, including the soil. Also, there is also a constant rise in demand for food, mostly gotten from plants. To attain this, the soil needs to be healthy to support the growth of plants. A healthy soil is thus one that is rich in and contains the correct proportion of nutrients, diversity of living organisms and supports plant growth. Living organisms such as earthworms help in stabilizing soil structure, good drainage and ensuring nutrients availability. Soil microorganisms such as *Azotobacter* spp. and *Bacillus* spp. also play a huge role in breaking down and ensuring that nutrients such as nitrate, iron and phosphorus are available in forms that can be assimilated by plants. Others such as *Pseudomonas* spp. breakdown pollutants to useful forms, thereby making the soil conducive for living organisms. This chapter thus looks at the factors that promote soil formation, health and biodiversity while also proffering methods to improve soil health such as the introduction of soil-health promoting living organisms.

Keywords Soil structure · Soil microorganisms · Soil formation · Soil health · Nutrient availability

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1 Basic Concepts of the Soil

Soils are essential and operational component of terrestrial environments. It is generally well-known as earth, it is a combination of gases, water, minerals, organic matter and organisms (microorganisms and macro organisms) that provide living support to soil microbes and plants. The phases of the soil are made up of the solid phase (of organic matter and minerals), the liquid phase (that hold the water and salts) and the gas phase (made up of air) [1]. The soil serves as a cistern of nutrients and water, a channel of disintegration and percolation of wastes, and as a contributor in cycling of nitrogen, carbon and other element via the universe ecosystem [2]. Several factors including climatic influence, presence of organisms, environmental terrain (slope, elevation and orientation of soil environment) and the parent materials of the soil affect the formation of the soil. The soil continues to experience development through weathering processes driven by biological, physical, climatic, topographical and chemical processes which include weathering with associated erosion [2, 3].

2 Components of the Soil

Management of nutrient is a vital feature of soil composition. The basic components of soil and their approximate percentages include minerals (45%), organic matter (5%), water (25%), and air (25%) (Fig. 1). The soil composition can vary daily and this is dependent on the kind of soil, availability of water supply and cultivation practices. Soil minerals and organic matter's functions in the soil is to retain and accumulate nutrients while soil water increases the uptake of available nutrients by plants, also the soil air provides the required air for microorganisms to carry out biological activities for the distribution of more nutrients into the soil [4].

2.1 Soil Minerals

Soil minerals are important in soil fertility since mineral surfaces function as prospective sites for storage of nutrients. Different quantities of nutrients abound in various types of soil minerals. Numerous types of minerals are present in the soil in varying sizes and chemical composition. Particle size is a vital property that distinguishes different soil minerals. Soils contain particles ranging from large to tiny particles [4].

Soil minerals are available in two forms: primary minerals and secondary minerals [5]. Primary minerals (parent materials) are broken down and disintegrated through physical weathering. Physical weathering is caused by erosion, wetting and drying of rocks, action of plants and animals, falling or breaking of rock materials into smaller pieces [4]. Primary minerals form at high temperatures from igneous and metamorphic rocks in the soils. They include K-feldspars, micas, quartz, pyroxenes

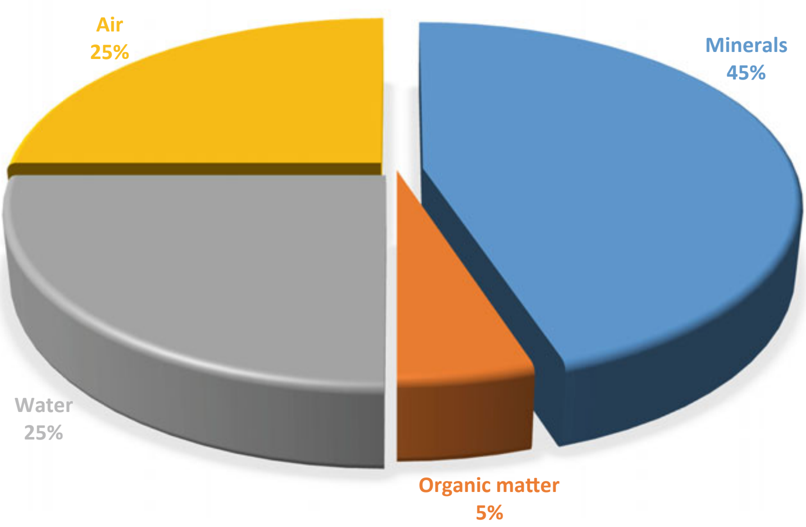

Fig. 1 Composition of soil [4]

and hornblendes. Primary minerals serve as vital reservoirs of a number of micronutrients such as Ca, Na, Si, K, Mg and Fe. The physical weathering of primary minerals results in the release of a number of nutrients into the soil solution [5].

Secondary minerals are generally formed by low-temperature reaction during the chemical weathering of primary minerals in the soil [5]. Chemical weathering involves the transformation of primary minerals into secondary minerals. Small particles in the soil can be synthesized from secondary minerals and there may be accumulation of residual materials from unweathered materials [4].

2.2 *Soil Organic Matter*

The organic matter component of soil is referred to as the soil organic matter. The soil organic matter is made up of living and dead microbes, remains of plants and animals, decomposing plant and animal debris at different phases as well as cells, tissues and metabolites of soil microorganisms [4, 6].

Soil organic matter include majorly the living and non-living constituents. The living constituents consist of the dormant or active soil microorganisms and soil macro organisms while the non-living component is gotten from the inputs of dead animals and plants into the soil. Different biogeochemical processes take place on these constituents which can either be transformed, preserved or lost in the soil. Generally, the non-living constituent of the soil organic matter is believed and known to compose biologically-derived molecules that undergo biological and chemical degradation [7]. Currently, microorganisms are well known to contribute immensely to soil organic matter formation [8].

Soil microorganism decompose organic matter in the soil resulting in the respiration of CO_2 to the atmosphere, however, some CO_2 are assimilated into microbial biomass, or is broken down to some extent, or could interact with soil minerals and remain in the soil. Interaction between soil organic matter and soil minerals occurs, hence, bringing about the formation of organic matter–mineral complexes and this contributes to soil aggregation, thereby increasing the stable conditions of soil organic matter by preventing microorganisms from accessing organic matter through the organic matter–mineral interactions [9].

Microorganisms, plant and animals depend on organic matter as their source of energy and nutrients. Bacteria and fungi utilize organic matter as source of energy, which are eaten by protozoans. The protozoans are consumed by other organisms in the soil such as arthropods, annelid, nematodes which are able to breakdown the raw organic matter. This process allows all organic matter to be processed as in a digestive system cycle and is referred to as soil food web [10].

Soil organic matter contributes several benefits to the soil which is particularly important for soil quality and functions. Such benefits include: enhances soil aggregation, improves the structure of the soil, improves water retaining capacity, increases the ability of the soil to withstand pH fluctuations, enhances microbial biodiversity in the soil, improves the cycling and storage of plant nutrients and increases the fertility of the soil by making available cation exchange sites as well as storing of important plant nutrients including micronutrients [11].

2.3 Soil Water

Water is coherently significant on the soil and it is universal. In addition to the importance of water to living things and the wellbeing of ecosystems [12], water is regarded as a necessity for life on other planets [13]. Soil water is the water content in the soil usually expressed as weight or in volume and can be quantified using the basic of remote sensing techniques and in-situ investigations [14]. Considerable amount of water can be processed and held in the soil. The soil is able to absorb water until a full capacity is reached or the rate of water transmission into the soil pores is exceeded usually referred to as saturation level or field capacity. Some of the water get removed from the soil into rivers and watercourses, however, a large quantity of the water (soil water) gets held up in the soil irrespective of the gravity, which is beneficial to organisms as well as plants, thereby impacting immensely the health of soils and efficiency of land [15].

Soil water is important to the soil in the following ways:

(i) Soil water is important for all forms of lives, including plants, macro organisms and microorganisms [4].

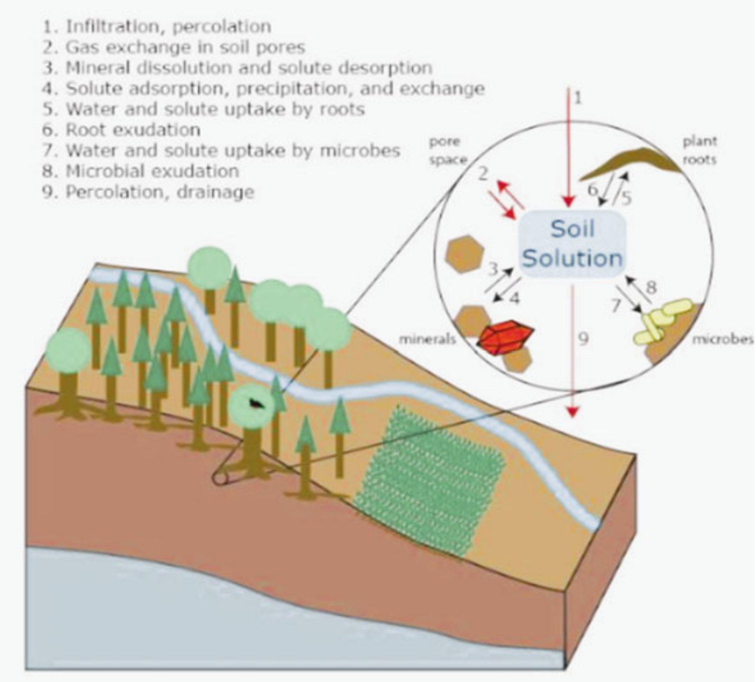

Fig. 2 Physical and geochemical processes associated with water in soils [17]. Arrows 1, 2 and 9 signifies physical processes; Arrows 3–8 signifies geochemical processes; Processes 1 and 9 [20]; Processes 3 and 4 [21]; Processes 5–9 [22, 23]

(ii) Most biogeochemical activities are carried out in soils as a result of the presence of soil water (Fig. 2). A lot of chemical reactions that regulate weathering processes and formation of soil take place completely in fluid [16, 17].

(iii) All plant nutrients are easily assimilated by plants in liquid water. Soil water contains dissolved substances (inorganic and organic matter) and nutrients, e.g. calcium, nitrogen, potassium and phosphorous resulting in growth of plants and crops [4].

(iv) The movement of solutes and gases in soils is possible in the presence of water. Soil water controls heat transfer, hence, facilitates the buffering of the temperature of the soil [18].

(v) Microorganisms require soil water in the pores of the soil to carry out metabolism [19].

2.3.1 Soil Water Holding Capacity

The movement and retention of water and gases in the soil profile occurs in the openings present between soil particles and this is referred to as pores. The particle size, structure of the soil, type of clay and organic content commonly determines the ability of the soil to retain water; sandy soil possess large particle and pore sizes, therefore, do not have the ability to hold water, there is an easier passage of water through the soil profile. On the other hand, smaller particle and pore sizes are present in clay and silt soils, leading to the retention of more water in the soil profile [4, 24].

Field capacity is a common term in understanding soil water holding capacity, it is the highest volume of water a particular soil can hold. Some soils do not hold water within its pores space, therefore, could remain dry and unable to provide water to plants, such soils are said to be at wilting point. Some other soils retain water which is made available to plant (available water) within the range between the wilting point and the field capacity [24].

Retention of water in the soil occurs when the adhesive force of attraction of water is stronger than the cohesive forces of water. Cohesive force allows water molecules to bind to each other thereby forming water droplets. Adhesion force causes water molecules to attract to solid surfaces. Water molecules show properties of surface tension where water molecules act as elastic films. Therefore, the combination of surface tension, adhesion and cohesion forces gives the term capillary action [4]. Capillary action results when the adhesion forces existing between water and solid is greater than the cohesion forces between water molecules. Capillary force regulates the movement and retention of water within the soil. This is because it allows the horizontal and upward movement of water within the soil profile rather than the downward movement caused by gravity [4].

2.4 Soil Air

Soil air are atmosphere within the soil and they contain gases in the air openings between the soil minerals organic matter and water. If the openings between the soil particles does not hold water, they are occupied with air. Carbon dioxide, nitrogen and oxygen are the main gases in the soil [25]. Plant roots and soil microbes utilize oxygen for respiration. Ammonia, nitrous acid, methane and nitric acid are the other pure gases contained in the soil [26].

As water is removed from the soil pore (through root absorption or evaporation), air fills the soil pores which aerates the soil. The entry of water into the soil pores blocks the aeration network. Hence, the soil air and water are frequently inversely related as they are functional component of soil: an increase in soil air results in decrease in soil water. In the same vein, a decrease in soil air causes increase in soil water. Therefore, an appropriate balance must be maintained between the soil air and soil water [4].

The composition of gases in the atmosphere is similar to that of the soil atmosphere (Table 1). The soil atmosphere refers to the composition of gases present in the pores of soils. The composition of gases in the soil varies daily or seasonally compared to the composition of gases in the atmosphere. This is as a result of the several processes (chemical and biological) that constantly take place in the soil. Despite these variations, soil gases have greater concentration of water vapor and carbon

Table 1 Composition of atmospheric air and soil air [27]

	Gas	Atmospheric air (%)	Soil air (%)
1	Carbon dioxide	0.04	0.25
2	Oxygen	20.9	20.6
3	Nitrogen	78.0	79.2

dioxide [27]. Furthermore, the concentration of other gases (e.g. nitric acid, nitrous oxide and methane) in the soil is significant even though it is lesser, they are involved in anthropogenic influence and determination of greenhouse gas flux [26].

The atmosphere of the soil is uniform all through the soil due to restricted compartment of air. Compared to most atmospheric humidity, the relative humidity of soil air is 100%. Soil air frequently contains more carbon dioxide [4]. Microbes and plant roots utilize oxygen which results in reduction of oxygen and increase in the concentration of carbon dioxide which is 10–100 times higher that atmospheric carbon dioxide, thereby resulting in inhibition of root respiration [28]. High levels of carbon dioxide are harmful. Through appropriate carbonate buffer systems, calcareous soils are able to regulate the concentration of carbon dioxide while acidic soils accumulate carbon dioxide in the pores spaces of the soil [29].

Plant roots and soil microbes release volatile organic compounds (VOCs) other than carbon and nitrogen oxides into the soil [30]. These VOCs are utilized as chemical cues, thereby transforming the soil atmosphere as the center of interactive networks which performs a significant part in the evolution, uniformity and dynamics of the soil environment [31, 32].

3 The Soil Profile

Soils show a vertical distribution with some variations from place to the other which could be as a result of the length of weathering, strength of parent rocks, geographical and environmental conditions. The existence of different minute vertical layers within the soil surface with distinct features compared to the layer above or below is known as soil horizons [33]. Soil horizons are commonly distributed as layers parallel to the surface of the soil. Therefore, a full section of soil containing a set of distinct horizons is referred to soil profile. The soil profile is a cross-section view of all the soil horizon and the kind of soil and rock that make up the soil profile [33]. There are five major horizons in the soil profile and are designated with letters O, A, E, B, and C [4] as shown in Fig. 3.

The O-horizon is a surface horizon which consists of mainly organic matter (e.g. remains of animals and plants) [4]. Various phases of decomposition (such as low, moderate, extreme and complete levels of decomposition of organic matter) can be observed in this horizon. As a result of the abundance of organic content, the physical appearance of the horizon is often dark brown or black. Litters of the roots of small grasses can also be found in this horizon [33].

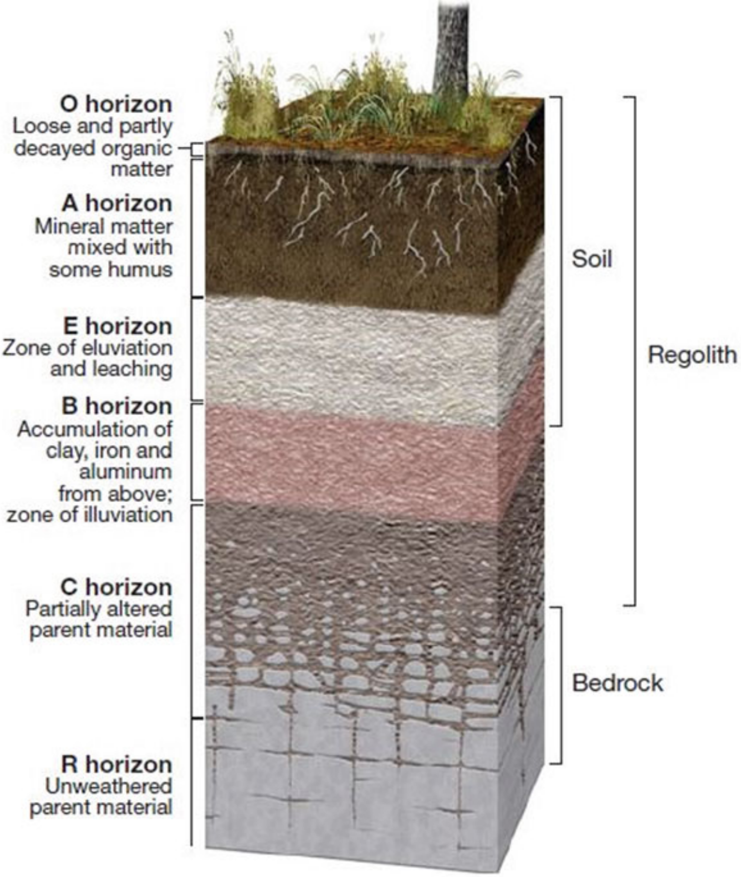

Fig. 3 Schematic diagram of the soil profile showing the different horizons [35]

The A-horizon is the topmost horizon contains different groups of microorganism and a deposit of humus mingled with mineral (silt, clay and sand) to form aggregate structures but does not consist of surface litter present [2]. The A horizon is the layer for most agricultural soils and grassland. It is referred as the root zone and is susceptible to water and wind erosion [33].

The E-horizon. This horizon is beneath the O and A horizon and has a lighter colour [4]. The horizon is enriched with soluble nutrients leached from the A and O horizon as a result of precipitation and irrigation, hence, it is also known as the eluviation zone. The E horizon is chiefly developed as a result of sandy parent material and elevated rainfalls [2]

The B-horizon. This horizon is developed beneath the horizons O, A and E and has high deposits of carbonates, silicate, iron, clay and aluminum precipitated into the horizon by chemical processes or by percolating water, therefore, the zone is also referred to the illuviation zone. The roots of large trees are found in this horizon [33].

The C-horizon. Beneath the horizons A and B is the C horizon, no soil structure is developed in this zone with little or no humus deposit. The unconsolidated, weathered and unweathered parent material found in the zone are utilized for the formation of horizons A and B [2]. Some geologic material and cemented sediment are present in the zone. Minimal activities take place in the C horizon, although, some additions and losses of soluble materials are notable. The horizon is also called saprolite [33].

Depths beneath the horizons O, A, B and C is the R horizon. It contains all types consolidated rock and unweathered parent material [33].

4 Process of Formation of Soil

The process of formation of soils is quite long, a slender stratum of soil is formed after several million years. The formation of soil is complex, this is because the soil is composed of different mixture of several component. The formation of soil involves the combined effect of weathering, development of the soil's structure, arrangement of the soil structure into horizons, and movement among others [34].

The process of soil formation include additions, losses, translocation and transformation. Firstly, decomposing vegetation, organisms or newly produced minerals are added to the soil, for example, water gets into the soil through rain, likewise organic matter gets into the soil through animal waste. Secondly, soil particles such as clay, silt, sand and organic matter gets removed from the soil as a result of the movement of water and wind which consequently changes the makeup (physical and chemical) of the soil. For example, evaporation of water into the air, washing away soil particles during storms, chemical breakdown of organic matter [34].

Thirdly, the conversion of organic matter as well as the chemical weathering of sand resulting into the formation of humus and clay minerals respectively is a process of soil formation known as transformation, for example, the decay of dead leaves to humus, weathering of rocks to clay. Fourthly, the movement of soil components from one horizon too the other is a process of formation known as translocation. This results in visual change in the physical and structural characteristics of the soil. Examples of translocation include the movement of water from top of the soil to the bottom through gravity, movement of minerals from bottom of the soil to the top by evaporating water, the movement of materials in all directions within the soil by organisms [34].

4.1 Specific Processes of Soil Formation

The specific processes involved in the formation of soil are as follows:

1. *Organic matter accumulation.* In this process, decaying plant and animal materials are accumulated in the soil. The process leads to the breakdown of the

organic matter to form humus and newly synthesized organic matter [36]. The organic materials accumulated may be stored in the root system in a well-drained soil and be further decomposed into the soil while in poorly drained soils, the organic materials get accumulated with slow level of decomposition as a result of water logging [34].

2. *Eluviation.* This involves movement of certain constituents of the soil such as clay and soluble salts from the upper area of the soil to the lower areas in the soil though the downward movement of water. The layer from which the materials have been removed is referred to the eluvial zone. As a result, the composition of the eluvial zone is altered (typically light-gray colour, with little amount of clay and organic matter) [34].
3. *Illuviation and transformation.* The process by which certain soil constituents washed from the upper layer of soil are deposited in the lower layer of the soil through percolating water is known as illuviation. The materials deposited in the lower layer of the soil include clay, colloids, silt, sand, soluble salts and other component of the soil. The deposited constituents undergo transformation, that is, chemical weathering of sand and silt resulting in a new physical and chemical composition of the soil layer [34].
4. *Podsolisation and translocation.* This process of soil formation is complex and it involves the dissolution of organic matter and aluminum and iron ions thereby forming organo-mineral complexes. These complexes are mobilized and translocated from the top soil horizon and deposited in the lower soil horizon with percolating water [37]. Through the process of podsolization, the topsoil soil (eluvial horizon) becomes bleached and shows an ash-grey colour while the lower soil (illuviated zones) becomes red, black or brown in colour because they accumulate organic compounds and sesquioxides. Typical podsols soils (soils formed as a result of podsolisation) are common in the Northern Hemisphere especially in the boreal and temperate zones [38].
5. *Laterization.* This is a prolonged soil formation process that occurs to soils in the tropical and subtropical regions. Laterization is a rapid process of weathering of rocks and minerals under high rainfall and temperature which leads to the leaching of soluble minerals and leaving insoluble minerals such as iron and aluminum resulting in the formation of the soil known as laterite. These soil types are rich in oxides of iron and aluminum and appear reddish-brown. These soil types are ideal for construction and building purposes because of their durability and hardness [34].
6. *Calcification.* This is a soil forming process that results in the accumulation of alkaline salts (calcium carbonate) on the surface of the soil. Precipitation of the calcium carbonate occurs in form of small crystals or large masses through downward movement of water, or upward movement of water by capillary action and the gradual accumulation of calcium carbonate in the soil which leads to the formation of calcified layers (caliche) in the soil profile [34].
7. *Gleying.* This process of soil formation is common in wet, cold and anaerobic conditions with the presence of reduced iron compounds which is either removed

from or concentrated in the soil leading to a blue-green coloration of the soil layer [34].

4.2 Factors Affecting Soil Formation

The genesis of soil, its rate and the kind of soil formed is dependent on some factors. During soil formation, nutrients are both added and removed from the soil over time. These factors include the topography of the land, climate, parent material, time and the biota present [39]. Soil is the result of the activities of living organisms and climate on the climate based on the condition of the topography or relief [40]. The influence and combination of these factors distinguishes the soil in point A from that of point B.

Topography: A slope's nature and drainage affect the soil formed from it. Erosion could occur easily in a steep slope causing it to lose its topsoil and become thinner in comparison with those in the bottom land which will likely have dark-coloured soils. Soils that are levelled rarely gain or lose materials since the soil is well-developed [40].

Climate: Precipitation and temperature influence the process of soil formation. Climate regulates the speed of physical and chemical processes as well as the type of weathering [41]. When the temperature is warmer, reactions occur faster including rock weathering. The climate also affects the kind of living organisms present in a region, thus affecting soil genesis.

Parent material: The type of parent material determines the mineral that will be present in the soil as it is the foundation for the soil's formation. This also determines pH, texture and nutrients in the soil. Consequently, soils formed on basalt will have more basic cations than granite, which will be acidic [40].

Biota: Living organisms such as microorganisms, animals and plants affect the formation of soil. Soil animals are able to mix soil materials forming pores and burrows which could destroy already formed soil horizons. Microbes increase chemical reactions and give off organic substances capable of increasing the infiltration of water in the soil. They decompose organic matter making the products available in soil. Burrowing animals including earthworms mix soil thus altering the physical features including increasing its permeability to water and air. These organisms have a huge influence on the physical and chemical environment of the formed soil. Anthropogenic activities such as fertilizer application and cultivation alter soil formation [42].

Time: The amount of time within which these factors operate determines the quality of the product Climate and biota act on the topography and parent material over a period of time as such this period of time tells the age of the soil [40].

5 Conceptual Knowledge of Soil Health

Soil health is the ability of soil to function within ecological constraints in order to sustain productivity, contribute to environmental quality, and support plant and animal health. The concept of soil health is considered using the indicators such as physical, chemical, and biological properties of the soil, as well as their interaction with each other and their environment [43]. These indicators can be used to test and evaluate the health of the soil in various places and the choice of indicators is based on their applicability to soil function and their capacity to offer farmers and stakeholders useful information [44].

Adopting of Soil Health Card (SHC) initiative has become one strategy that tries to give farmers knowledge about the nutritional status of their soil and suggestions for fertilizer application, however SHC initiative also presents difficulties, such as the inability to comprehend the data on the card and the inability to calculate fertilizer doses based on the soil's nutrient condition [45]. Farmers can overcome these difficulties and advance sustainable soil health management by receiving regular training on the collection of soil samples and the interpretation of recommended fertilizer doses [45].

For sustainable soil management, evaluating soil health is essential. Numerous indices, such Cornell's Comprehensive Assessment of Soil Health (CASH) and the Soil Management Assessment Framework (SMAF), have been established to assess the impact of soil management practices on soil health. These indices incorporate soil characteristics relevant to significant soil processes as carbon transformation, nitrogen cycling, and soil structure preservation. They also offer frameworks for evaluating the overall soil improvement or degradation brought on over time by various management practices [46].

Numerous ecological and environmental processes heavily depend on the composition and structure of the soil. While soil structure refers to the positioning as well as arrangement of soil particles as well as the pore spaces between them, soil composition relates to the types and proportions of various factors, such as minerals, organic matter, water, as well as air. The soil's texture, porosity, and permeability are crucial physical characteristics that affect the soil's quality and a number of environmental processes. The relative amounts of sand, silt, and clay particles in the soil are referred to as its texture and it is frequently employed as an indicator of soil quality [47]. Porosity of the soil is determined by the measurement of the gaps or empty areas in the soil that can hold either air or water and it is influenced by things like soil structure, compaction, and texture. Porosity influences soil nutrient availability, root penetration, and water storage capacity [48]. The ability of soil to convey water or other fluids is referred to as permeability and it is influenced by things like soil structure, porosity and texture [49].

In determining soil fertility as well as plant growth and production, chemical characteristics of the soil are very important. Numerous studies have examined how various elements affect the chemical composition of soil and how this may affect plant growth [50–52]. These studies show that chemical characteristics of soil play a significant role in affecting soil strength [50], microbial populations [51], plant growth and fertility [52]. Understanding and controlling the chemical characteristics of soil is crucial for environmentally friendly farming.

The biological characteristics of soil, such as microbial activity, biodiversity of the soil fauna, and soil organic matter, are essential for soil fertility, nutrient cycling, as well as the overall health of an ecosystem. Numerous elements, including management practices, the physicochemical makeup of the soil, the levels of heavy metals, and changes in land use, might affect these features. For sustainable soil management along with ecosystem preservation, it is crucial to comprehend the connections between these variables and biological features [53–55].

5.1 Diseases Associated with Soil

Soil microorganisms are crucial for soil ecosystems and are involved in nutrient cycling and soil fertility maintenance [56]. However, it is known that soil is connected to a number of diseases, including those spurred on by bacterial and fungal pathogens. For example, it has been discovered that adding pineapple leftovers to heavily affected soils with Fusarium wilt diseases can minimize the amount of pathogens there and the occurrence of the disease. Changes in particular fungal species that exhibit inhibitory effects against the pathogen are associated with the establishment of suppressive soils [57]. In another investigation, the effects of replanting American ginseng in reaction to disease outbreaks were examined. The findings demonstrated that compared to a new ginseng field, fungal communities in an ancient ginseng field were more responsive to the soil environment. Healthy ginseng plants were observed to alter fungal ecosystems in both fields by attracting possible disease-suppressing fungi. Pathogens became more numerous when these important populations and their members declined [58].

The prevalence and control of disease are also influenced by the bacterial composition of the soil. Certain bacterial taxa, including *Kaistobacter*, *Flavisolibacter*, *Sphingobacterium*, *Koribacter*, *Nitrospira*, *Bradyrhizobium*, and *Bacillus*, are more prevalent in soils connected to plants with reduced clubroot disease severity. This indicates the significance of management techniques that enhance soil's physical–chemical properties in order to control bacterial populations linked to disease suppression [59]. The microbial diversity and disease-suppressive activity of standardized commercial conventional soils and organically farmed soils for rice nursery cultivation was examined. It was discovered that while conventional soils revealed disease occurrence, organically farmed soils greatly inhibited the establishment of bacterial rice seedling disease [60].

Numerous viral pathogens that can infect plants, animals, and people can be found in soil [61]. Viral diseases such as tick-borne encephalitis and water-borne viruses are associated with soil. The tick-borne encephalitis virus (TBEV) can cause severe inflammation of the central nervous system and is spread to people by tick bites [62]. Water-borne viruses cause diarrhea as well as hepatitis A and E [63].

It is vital to know that diseases affecting soil can be as a result of both living and non-living environmental factors (biotic and abiotic diseases). Abiotic diseases are brought on by conditions like soil compaction, nutrient deficits, and temperature, whereas biotic diseases are brought on by live organisms like fungi, bacteria and virus [64].

5.2 Maintaining a Healthy Soil

In order to perform sustainable agriculture and protect the environment, healthy soil must be maintained. It has been demonstrated that conservation tillage methods, such as minimum tillage with residue retention (MTDR) and no-tillage with residue retention (NTDR), enhance the physical and chemical characteristics of soil and decrease nitrogen and phosphorus losses in agricultural fields. These methods are suitable for enhancing soil health and decreasing agricultural pollution because they help retain soil nutrients and reduce nutrient runoff and drainage water losses [65].

Utilizing plants and microbes in soil remediation has been found as a low-cost and sustainable method for securing and cleaning up polluted places while retaining soil ecological services [66]. This method reduces hazards and encourages long-term soil sustainability by making use of the inherent properties of plants and microbes to stabilize contaminants and restore soil health.

Applying organic fertilizers, such as water-soluble fertilizers, has been shown to greatly promote soil carbon storage, increase soil microbial diversity, and improve the soil microbial habitat [67]. Water-soluble fertilizers have a positive effect on soil health and crop output by increasing soil nutrient status and reducing soil acidity.

Agroforestry, the use of organic fertilizer, and the construction of stone-faced soil bunds alongside vegetative measures are examples of sustainable integrated land management practices that can be used to effectively reduce nutrient loss and monetary loss while also promoting conservation of water and soil [68].

5.3 Relevance of Good Soil Formation to Soil Health

The health of the soil is directly related to good soil formation. Physical, chemical, and biological characteristics that support soil's ability to sustain production, preserve environmental quality, and advance plant and animal health are also related to good soil formation [43]. For agriculture to be sustainable and to provide food security, effective management practices must be used to improve soil health and quality [69]. Considering a variety of biological processes and ecosystem functioning, good soil formation is essential. Climate, geology, vegetation, as well as biological activity are also variables that contribute to soil formation [70].

Additionally, the emergence of various soil types, such podzols, can help form healthy soil. The production of podzols on various aged coastline bars of Lake Ladoga in Russia was examined [71]. The study concentrated on soil chronoseries found on four different ages of coastline bars. The study looked at how organic matter stored up and changed in various soils. For the formation of soil and nutrient cycling, it is essential to comprehend the processes of organic matter development and change.

Furthermore, climate change and the addition of organic matter are a few of the variables that have an impact on the formation of healthy soil. Climate change has the potential to affect soil erosion rates [72]. The fertility of the soil can be increased and its physical, chemical, and biological qualities can be improved by the addition of organic matter, such as tofu dregs [73]. Evidently, for soil to remain healthy, it needs to be formed properly.

6 Soil Biodiversity

Soil biodiversity refers to the diversity of living things found in soil which includes a wide range of creatures that are invisible to the unaided eye, including microorganisms, meso-fauna, and macro-fauna. Based on their symbiotic relationships and interactions with other soil elements, plant roots can also be regarded as soil organisms [74].

A huge variety of organisms inhabit the soil environment. The abundance of these species that are found can often be extremely high. The level of diversity and richness is unique to soil type and influenced by factors such as soil texture, pH, organic matter content and utilization of the soil. In an examination of temperate grassland soil, both the number and variety of organisms can be categorized into size-based groups such as microorganisms (Archea, Bacteria, Algae Fungi) Microfauna (Protozoa, Nematodes) responsible for recycling organic and inorganic chemicals into forms that are readily accessible to plants and other creatures; mesofauna which are vital to the food chain together with other groups, increasing their supply of energy and nutrients, mostly nitrogen; and megafauna such as earthworm, ants, woodlice. They influence the soil's porosity, affect how water and gas travel through it, and bind soil particles, reducing soil erosion [74].

6.1 Effects of Soil Biodiversity

Microorganisms have significantly contributed to the rich and complicated interactions among soil organisms because of their enormous diversity, massive populations, and extensive evolutionary history [75, 76]. These connections range from widespread mutualisms to highly particular symbioses within the soil ecosystem could result into recycling of nutrients within the soil, formation of soil and weathering, waste recycling by saprophytes, detritivores, fungi, bacteria and actinomyces, functional redundancy, plant health enhancement, regulation of soil organic matter and modification of soil structure which could lead to habitat formation for other microorganisms [74].

6.1.1 Bacterial Diversity in the Soil

The diversity of soil bacteria is enormous, and a variety of biotic and abiotic factors can have an impact on the composition and diversity of soil bacterial communities [77]. The diversity of soil bacteria may vary or improve as a result of human actions on land use [78]. Various bacteria groups are present in the soil as decomposers. Bacteria such as *Pseudomonas fluorescens*, *Bacillus subtilis* are useful soil bacteria that breakdown simple sugars, carbon, and organic substances. By collaborating with plants and nitrogen-fixing bacteria for example, *Azotobacter, Clostridium*, *Rhizobium, Mesorhizobium*, *Klebsiella* spp., they aid plants in absorbing certain nutrients from the soil and guard against illness. Plant diseases are caused pathogens such as *Xanthomonas* sp., *Erwinia carotovora*, and *Streptomyces* scabies. Bacteria for example the lithotrophs are capable of suppressing diseases in plants. They include *Bacillus megaterium* and *Pseudomonas fluorescens* which can be used to combat *Rhizoctonia solani* disease; *Bacillus subtilis* to combat *Alternaria helianthi* seedling blight of sunflowers) [79].

Functions of bacteria in the soil include production of polysaccharide, which aids in binding sand, silt, and clay particles together to form micro aggregates and improve soil structure [80], release of nitrogen and nutrients to the soil and plants, stimulating plant growth by producing plant hormones and secreting enzymes to make phosphorus soluble in soil and available to plants, and helping to improve the soil so that new plants can be established [81].

6.1.2 Fungal Diversity in Soil

Fungi are microbes that play a significant role in the breaking down reactions which occur place in the soil; they aid in the disintegration and absorption of lignin and the cellulose found in plant cell walls. Saprophytes, arbuscular mycorrhizal fungus (*Glomus* sp.), are among the beneficial fungi in soil [82]. Molds and mushrooms are saprophytes that produce fungal biomass, CO_2, and minute molecules from decomposing organic materials. They help the soil retain nitrogen and remain immobile. Some fungi can be referred to as mutualists (mycorrhizal fungi). They are able to symbiotically penetrate plant roots either as ectomycorrhizae, which normally develop on the outside of roots and are attached to trees or endomycorrhizae that reside inside plant roots. These fungi build a mesh with the help of their hyphae, which helps to stabilize soil aggregates and improve the physical soil structure. Furthermore, these fungi are capable of expanding the root's surface area, enabling the plant to access nutrients and water. They help deliver phosphorus from the soil to the roots, also known as ecosystem regulators [83].

6.1.3 Algal Diversity in the Soil

The main significant non-aqueous environment for algae and cyanobacteria is the soil [84]. As a result of the great ability of algae and cyanobacteria to adapt morphologically and physiologically to various environments, they normally serve as prototype microorganisms in the soil [85]. There are several thousand different species of algae ranging in size from few microns to tens of meters. The population of algae in the soil usually ranges from 10,000 to 100,000 cells in one gram of soil. The source of energy of algae is obtained from the sun via photosynthesis thereby making their own food [86], and include cyanobacteria (prokaryotic organisms) and diatoms, green algae and euglenoids (eukaryotic organisms) [87, 88]. As a result of algae being photosynthetic, they play a vital role in the introduction of organic matter into the soil and excretion of polysaccharide which improves the aggregation of the soil. Diatoms have a preference for well-drained soils rich in organic matter, the green algae prefer wet, non-flooded acidic soils while the cyanobacteria are mostly found in dry areas such as polar and desert regions [86]. Algae play important roles in the soil, they include:

(i) They improve the soil fertility. When algae die, they adds organic matter to soils, resulting in the reduction and prevention of soil erosion [89] and contribute to the growth and protection of plants, as well as provide substitute to lessen the need for chemical fertilizers and pesticides [90]. Predominantly, cyanobacteria are considered biofertilizers as a result of ability to fix nitrogen [91]. Genera *Anabaena*, *Nostoc*, *Calothrix*, *Scytonema*, *Schizothrix* are most commonly known nitrogen-fixing species [92].

(ii) Some algae, for example, the blue green algae fix atmospheric nitrogen. Environmental and physiological factors such as concentration of organic and inorganic sources of nitrogen, ambient temperature and light intensity, determine the amount of nitrogen fixed by the organisms [93].

(iii) Plant growth is greatly promoted through the beneficial capacity of algae in soil nutrient cycling which improves the availability of nutrient in the soil [94, 95].

(iv) Important growth-promoting substances such as organic acids, amino acids, vitamins and hormones are produced by soil algae capable of forming root associations or protect plants against pest and phytopathogens [96–98].

(v) Soil algae produce polysaccharides which increases soil structure, aggregation, water-holding capacity and porosity [99]. Soil algae also improves the quality of soil by ameliorating in the reclamation of saline and metals from the soils [100].

6.1.4 Protozoa Diversity in the Soil

Soil protozoa comprise ciliates, amebae (naked amebae and testate amebae), flagellates, sporozoans and microsporidia based on their mode of feeding and locomotion. Approximately 1600 different species of protozoan are well-known in the soil and have a record trail of survival within the soil environment. More number of species of soil protozoa (about 4000 species more other soil microorganisms) have been recorded. Around 10,000–100,000 individual protozoa have been noted in a gram of soil and this varies from one soil type to another [101].

Protozoa are unicellular eukaryotic microorganisms and are essential component of the soil ecosystems. This is because of their ability to consume a significant portion of the bacterial productivity thereby enhancing nutrient cycles and the flow of energy thereby benefiting man, animals and microbes [102]. Small protozoa such as flagellates consumes over 80% bacteria present in the soil, while in turn, larger protozoa such as ciliates feeds on the small protozoa. The protozoa does not require as much nutrient as a bacterium, consumption of a bacterium leads to excretion of excess nutrients in plant-available form. Both plants and other microbes utilize these nutrients. Therefore, there is a constant cycling of nutrients in the soil [103].

Ciliates and flagellates are capable of moving in the free water in the soil because they possess distinct and constant cell shapes. On the other hand, amoeba possess a more plastic bodies which that change shape continuously, therefore will require surfaces on which to move. Flagellates are the oldest group of protozoans and have simple cell structure. They can move by utilizing about eight flagella for swimming and for creating a feeding current for capturing bacteria which are taken to the bottom of the flagella and digested [104].

Ciliates are the youngest group of protozoans and have a more complicated structure than the flagellates. Fur-like cilia that cover the whole body surface in district patterns are found in ciliates. The cilia is used to filter out and direct food particles to the cytopharynx. The motion created by the cilia disturb bacterial films, which results in the release of bacterial cells into the aqueous phase of the soil which can then be consumed [105].

Amoeba have an uncertain history of evolution and they are into two categories: testate and naked amoeba. Testate amoeba are found in wet and acidic soils. They possess proteinaceous shells and are about 20–80 μm. The active individual amoeba extends out its pseudopodia over the aperture in order to aid movement and feeding. High numbers of testate amoeba have been described to possess substantial effect when studying nutrient turnover [106]. Naked amoeba have a loosely shaped body and are about 15–100 μm. In order for naked amoeba to feed and move, they require food within a water film on a surface for convenient change in its cytoplasm around a bacteria by pushing the pseudopodia forward and retracting pseudopodia backwards. Some species of naked amoeba collects and transport the cell to be digested in feeding cups [105, 106].

6.1.5 Viral Diversity in the Soil

The abundance of soil viruses is high and they play vital roles in soil ecosystem and the management of host dynamics [107]. About 10^8 viral particles can be present in a gram of soil and the wide-range of viruses present in the soil can influence the growth of plants in diverse ways [108].

Soil viruses are of great importance in the soil in the following ways:

(i) They possess the ability of mediating transfer of genes between hosts which is a potential cause of microbial mortality. This results in changes in the turnover and concentration of gases as well as nutrients thereby influencing the soil's ecosystem [108, 109].

(ii) Some soil viruses can infect microorganisms in the soil, hence affecting the functioning of other soil microbial to benefit the soil [108]. Majority of viruses in soils are phages which are capable of infecting bacteria, fungi, arheaea, nematodes, protists, annelids, burrowing animals, arthropods and plants. Bacterial viruses are commonest in the soil given the high population of bacteria in the soil [110]. For example, the effect of rhizobiophages on the legume-rhizobia symbiosis can impact the flux of soil nitrogen. Rhizobiophages are phages that infect rhizobia and such rhizobiophages can play vital roles in rhizobial ecology within the soils such as reduction of nodulation thereby influencing nodulation competition by phage-sensitive rhizobia [111].

(iii) Soil viruses contribute to nutrient cycling among the microbial population in the soil [108]. Through photosynthesis, plants fix atmospheric carbon which provides organic carbon into the soil. The organic carbon is decomposed by soil microbes and converted to mineral-bound forms of carbon or into biomasses resulting in respiratory losses. However, the amount of labile carbon is increased by soil viruses, thereby improving microbial respiration and production in soils [112]. Furthermore, soil viruses are also involved in recycling of other nutrients including sulfur, nitrogen and phosphorous [111].

Soil pH, soil water and temperature are important factors that affect the abundance of soil viruses.

Soil pH is an important environmental factor that affects the attachment of viruses to the surface of the soil, therefore affecting the persistence and abundance of viruses [113]. Soil water content is a major environmental parameter affecting both bacterial and viral abundance in the soil. As the soil water content reduces, viruses are tugged into small pores through decrease of the water film, however, as soon as the soil water increases, the viruses are released and repeated cycles of replication is initiated. Temperature also influences the persistence and abundance of viruses in the soil. The persistence and abundance of viruses in the soil is fostered with lower temperatures, however, high temperatures lead to thermal decay of viral particles [114].

6.2 *Effects of Unhealthy and Poorly Formed Soils on Soil Biodiversity*

Soil biodiversity, encompassing the diversity of microorganisms, plants, fungi, and animals living within the soil ecosystem, is a fundamental component of terrestrial ecosystems. It plays a pivotal role in ecosystem functioning, nutrient cycling, and overall ecosystem resilience. The health of soils, defined by their physical, chemical, and biological properties, directly influences the composition and abundance of soil organisms. This chapter aims to comprehensively examine the effect of unhealthy and healthy soils on soil biodiversity, exploring their intricate relationships, underlying mechanisms, and the implications for ecosystem sustainability. Healthy soils are soils that have the capacity to function as a vital living ecosystem which can sustain living organisms (plants, animals and humans), and connects agricultural and soil science to policy, stakeholder needs and sustainable supply-chain management [115]. Substantially, unhealthy soils are characterized by degradation resulting from factors such as pollution, erosion, compaction, and unsustainable land management practices [116]. High accumulation of Al, Fe, or Mn due to lower soil organic matter is a huge challenge thereby resulting in the reddish coloration of the soil [117]. These detrimental processes negatively impact soil structure, nutrient availability, and microbial activity, ultimately affecting soil biodiversity. For instance, soil compaction reduces pore space, limiting the habitat for soil organisms. Researches have emphasized how compaction hampers earthworm activity, essential for soil structure improvement and organic matter breakdown, consequently leading to reduced microbial diversity and nutrient cycling [118]. Furthermore, chemical pollutants like heavy metals and pesticides disrupt soil microbial communities, affecting their composition and function. Researches have shown that certain pollutants can inhibit specific microbial groups, altering microbial diversity patterns [119]. Excessive fertilizer application can also lead to nutrient imbalances, favoring certain plant species over others, and indirectly influencing the composition of soil biota. Nutrient availability in shaping plant-microbe interactions is important, which subsequently influence soil biodiversity [120].

6.3 Importance of Healthy and Adequately Formed Soils on Soil Biodiversity

In contrast, healthy soils are characterized by well-structured soil aggregates, optimal pH, nutrient availability, and balanced microbial communities [121]. Such soils provide a conducive environment for diverse soil organisms to thrive, contributing to ecosystem services [122]. Microbes in healthy soils play a critical role in organic matter decomposition and nutrient cycling. The positive feedback loop between plant diversity and microbial diversity, as diverse plants support a diverse soil microbiome has been highlighted [123]. The role of mycorrhizal fungi in nutrient uptake further accentuates the importance of healthy soils [124]. Arbuscular mycorrhizal fungi (AMF) form symbiotic associations with plants, enhancing nutrient acquisition. This relationship facilitates the transfer of nutrients and carbon between plants and fungi, promoting plant diversity and ecosystem stability [125]. Additionally, comparative analysis of multiple studies reveals consistent patterns in the relationship between soil health and biodiversity. Healthy soils support a complex trophic structure, involving macrofauna like earthworms and microfauna such as protozoa [126]. These soil organisms interact with plants, influencing nutrient cycling, organic matter decomposition, and disease suppression [127]. This, in turn, sustains higher plant diversity and resilience against environmental stressors. Unhealthy soils experience reduced microbial diversity, impacting nutrient availability, carbon cycling, and plant growth. The implications of soil biodiversity on ecosystem services are profound [128]. Healthy soils contribute to enhanced crop productivity through improved nutrient availability and water retention. Diverse AMF communities can lead to increased plant growth, highlighting the potential for sustainable agricultural practices [129]. Moreover, soil biodiversity plays a role in carbon sequestration, regulating greenhouse gas emissions and mitigating climate change impacts.

In conclusion, the effect of unhealthy and healthy soils on soil biodiversity is a complex and multifaceted relationship. Unhealthy soils, impacted by degradation and pollution, undermine soil structure and microbial communities, leading to reduced biodiversity. On the other hand, healthy soils, characterized by balanced nutrient levels and diverse microbial communities, foster a thriving and interconnected ecosystem. Comparative analysis underscores the critical role of soil health in shaping soil biodiversity, which in turn influences nutrient cycling, plant diversity, and ecosystem resilience. The implications for ecosystem services, agricultural sustainability, and global climate change mitigation highlight the urgency of prioritizing soil health to ensure the persistence of diverse and productive terrestrial ecosystems.

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Topsoil Regeneration and Bio-sequestration

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Abstract Soil regenerating is a type of ecological regeneration within the field of restoration ecology, it is the process of creating new soil and rejuvenating soil health by minimizing topsoil loss, maintaining greater amounts of carbon than becomes depleted, increasing the environment, and maintaining proper water and nutrient cycling. This has several advantages, including soil carbon retention in response to the rising danger of climate change, reduced risk of soil erosion, and greater overall soil resilience. Soil restoration is the procedure of enhancing its nutritional value by the addition of biological material that aids in discharge, absorption of water, and plant nourishment. Soil regeneration farming is the practice of restoring minerals and biological material of soil in order to increase the growth condition and production. We will interrelate top soil regeneration with bio-sequestration, a novel and fascinating method that uses nature's power to lower the quantity of molecules of carbon dioxide (CO_2) of following surrounding environment. It mainly undergoes natural procedure where CO_2 taken off from environment and accumulated in organic materials such as vegetation and soil. The technique of retaining carbon in a carbon pool is known as carbon sequestration (or carbon storage). Carbon sequestration occurs naturally, but it may also be done by technology, such as in capturing and storing carbon projects. Carbon sequestration may be classified into two types: geologic and biotic (also known as bio-sequestration).

Keywords Soil regenerating · Nutrient cycling · Soil resilience · Bio-sequestration · Geologic · Biotic

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1 Introduction

1.1 Structure of Top Soil

Formation of top soil is very slow process; it takes centuries to form soil layer which is formed by weathering of rocks with addition of plant and animal debris. It enriches the top layer of soil with nutrients of the plants. Naturally soil investigations are challenging and it gets harder to determine the relative relevance of organisms and minerals of soil to transfer in the soil formations. A review concluded that direct drilling is the optimum technique for semi humid and arid locations, as well as places where soil destruction by water is a trouble [7]. Then structure of topsoil can vary based on several factors, including climate, parent material, and vegetation. However, it typically consists of four main layers:

1. O-Horizon (Organic Layer): This is the uppermost layer of the soil, composed mainly of organic matter. It consists of decomposing leaves, twigs, plants, and other organic materials. The O-horizon provides nutrients to plants as it continually decomposes and adds organic matter to the soil.
2. A-Horizon (Topsoil): The A-horizon is the next layer and is commonly referred to as topsoil. It is typically darker in colour and richer in organic matter than the layers below. This layer contains minerals, humus (partially decomposed organic matter), and live organisms like earthworms and microorganisms. It is considered the most fertile layer and is crucial for plant growth.
3. E-Horizon (Eluviation Layer): The E-horizon is found beneath the A-horizon and is often referred to as the eluviation layer. It is characterized by the leaching of minerals, clay, and organic matter from above. This leaching process occurs due to intense rainfall or irrigation, which carries away nutrients and organic material. The E-horizon is usually lighter in colour and less fertile than the A-horizon.
4. B-Horizon (Subsoil): The B-horizon is below the E-horizon and is commonly known as subsoil. It can vary in composition but often contains accumulated minerals, clay, and other materials that were leached from the layers above. The B-horizon is usually denser and less fertile than the upper layers. It acts as a transition zone between the topsoil and the more solid rock layers below.

It is important to note that these layers can vary in thickness and composition depending on the specific location and environmental conditions. Additionally, there can be variations and additional layers such as the C-horizon (parent material), which is the layer of weathered rock or weathered material from which the soil is derived, and bedrock, which is the solid rock at the bottom of the soil profile.

1.2 Characteristics of Top Soil

The topsoil's bottom limit is fixed at 30 cm depth or, if shallower, at a root's growth limiting layer. This layer could be solid rock, a pseudo-genetically indurated layer and a chemically unfavourable layer or a layer with great contrast. Litter if present, is found above the topsoil. Organic content, organic matter status, physical, chemical, and biological properties, drainage characteristics, utilization of land, erosion or deterioration, external physical circumstances, and slope class are the primary features of top soils.

1.2.1 Physical Properties of Top Soil

Colour, appearance, framework, permeability, volume, uniformity, aggregate stability, and environment temperature are following physiological features in soil. These traits affect how some processes work including in the rate of infiltration deterioration, nutrient metabolic pathways and biochemical process.

Texture

Topsoil texture, 0–30 cm or shallower from sand to clay, infiltration decreases while water-holding capacity increases. Both permeability and capacity for holding water are high in organic soils. The texture of soil is typically classified into three classes depending on particle size and constituents: Small is clay, medium is slit, and large is sand. Sandy top soils, loamy top soils, clayey top soils, and organic top soils are all types of top soils.

Clay soil: It is composed of very fine mineral particles with little space between them and holds moisture very well. The clay soil is generally alkaline in nature and restricts nutrients from soil to flourish, resulting in a high yield. The crops that can be grown in this type of soil are broccoli, kale, Brussels, peas, cauliflower, fruit trees, ornamental, plants perennials, shrubs Helen's flower and flowering quince.

Silty soil:

Silty soil has physical features similar to both clay and sand and can hold a lot of water. As a result, silty soil is extremely fertile and rich in nutrients. When wet, this soil is slippery, yet it is not gritty or rough. These silts originate as a result of rocks being worn and washed off by liquid or ice. Vegetables, creepers, grasses, shrubs, perennials, and trees such as willow and birch can all be cultivated in this type of soil. Root vegetables such as carrots and other desert plants cannot be cultivated in this sort of soil.

Sandy soil:

Table 1 Different types of soil and its particle size

Soil type	Particle size
Sand	0.05 mm–2 mm (10×)
Slit	0.002 mm–0.05 mm (10×)
Clay	<0.002 mm (1000×)

Sandy soil is a type of soil with a gritty texture that is found all over the world, especially around arid and semi-arid locations. It is cohesion less and has a thin and loose structure that is primarily employed in building. The PH of sandy substrates ranges from 7.00 to 8.00, which boosts soil aeration, improves Drainage in tight soils, and promotes plant development. Various types of soil and its particle size is shown in the Table 1.

The systematic arrangement regarding soil granules in soil, equivalent as the capacity in each of the soil particle which combine altogether to form aggregates, are characterized with the soil composition. Aggregation has particular consequence in water and respective air transportation where it in turn has a consequence on the fluctuation in substances and impurities, furthermore biologic procedure, including growth of vegetation. The amount and type of biological material, which provides food for soil microorganisms like fungi and bacteria and their secretion of connecting substances (polysaccharides), the presence of enhancing agents like iron and oxides of aluminium, and vegetation, which turns into biological material and attaches soil particles collectively through roots, all have an impact on the formation of soil structure.

Soil Tensile Strength

The organic and mineral composition of a soil, in addition to its structure, are related to soil density. The most typical gauge of soil density is its overall density, which is calculated as the ratio of a topsoil's weight to volume. This weight-per-volume measurement is often expressed in grams per cubic centimetre (g/cm^3). Bulk density is a useful indicator of the total amount of porous space that is attainable within certain soil layers since it has an inverse relationship with pore space. Because biological stuff has a lower particle density than minerals, soils with higher levels of biological material have lower bulk densities.

Porosity of the Soil

The area of a soil's bulk volume known as the pore space is an open area that is home to gases or water but is not covered by inorganic or organic materials. The relationship between bulk density and soil porosity is inverse. A fertile, medium-textured soil typically has a total pore space that makes up around 50% of the soil's volume. Ranges of soil porosity are shown in the table that follows. However, permeability minus field capacity does vary, with larger values for soils with coarse texture (like sands) despite the fact that porosity does not significantly differ amongst soil textures. Porosity less field capacity, which is regarded as the upper limit of plant accessible water, represents the pore space that remains after gravity draining water from a soil.

Soil Cohesiveness (Plasticity)

Soil cohesiveness is one of physical property where it categorised in to finely grained with lower strength and which easily separable soils so that it is having a crucial tendency between particles for adhere purpose. The cohesive soils mainly classified by number of fine silts and by weight which exceeds up to 50%. Sandy clay, organic clay, clayey silt, silty clay are the major examples of cohesive soils.

Cohesive soil is having essential role in in its strength and which by following it exhibits the nature of plasticity. Based on three major sources the cohesion between soil particles depends upon cementation, electrostatic attraction and electromagnetic attraction and with the following primary valence bonding and adhesion [40]. In cohesive soil the engineering aspect of soil behaviour is having importance in its soil structure. The geometric arrangement mainly depends on genetic, chemical, mineralogical characters, stress conditions of soil and mineral particles. Comparing with non-cohesive soil the cohesive soils interparticle force is much higher.

1.2.2 Chemical Properties of Top Soil

For instance, pH, capacity for cation exchange, base saturation in order salinity, sodium adsorption proportion, enzyme activity, and conductivity of electricity are all examples of soil's chemical characteristics or properties. Concentrations of particular chemicals, such as phosphorus, carbon, nitrogen, major ions (calcium, sodium, magnesium, and potassium), sulphur, and trace metals and elements, are also among them. These characteristics have an impact on the nutrient cycle, biological activity, development of soil, pollutant fate, and erosion. The alkalinity or acidity of soil which is determined from the pH of soil. It is a major soil characteristic that affects metal mobility, soil microbial activity, plant adaptation, and nutrient availability. The correct amount of fertilizer that contains nitrogen, and cropping methods that boost soil biological matter and general soil health may all help managing the soil pH.

1.2.3 Biological Properties of Top Soil

Organic matter in the soil enhances soil structure while also increasing the ability to retain nutrients and water. Additionally, organic matter provides nourishment for soil microbial life. Decaying material, soil microorganisms, and the presence of pathogenic organisms. Some of the main components that influence the biological characteristics of top soil are Respiration rate, CO_2 evolution in a typical laboratory or in the wild. N/C mineral formation can understand the standard laboratory settings, a rise in the mineral's Nitrogen or Carbon content. Taking Earthworm volume, we can observe the number of worms per square inch. The Bacterial biomass refers to the total number of bacteria present in a given quantity of soil. Functional categories or genetic diversity can be used to characterize bacterial diversification and the Pathogen detection by using several pathology methods ranging from cultures to DNA analysis.

1.3 Soil Fertility

The potential of soil to support the development of agricultural plants is referred to as soil nutritional value. It can be achieved by supplying nutrients in right quantities and qualities over a sustained period of time. Crops require mainly nitrogen, phosphorus, potassium and other nutrients at right levels to get good yield. The capacity of soil to sustain plant development and deliver necessary nutrients is referred to as soil fertility which is necessary for development in healthy plants. When the soil is fertile, it contains the right balance of essential nutrients, organic matter, and microbial activity to promote optimal plant growth and high agricultural productivity [7].

Fertile soil is characterized by several key factors:

Nutrient availability: Fertile soil contains an adequate provision of micronutrients and critical plant nutrients including nitrogen, phosphorus, and potassium (K). These nutrients are necessary for the development and growth of plants. Their availability in the soil is crucial for healthy plant growth and high crop yields.

Organic matter: Soil fertility is closely tied to the presence of biological matter, which includes animal and plant remains that have decayed. Enhancing the structure, water-holding ability, nutrient retention, and other soil properties with organic matter microbial activity. It also serves as a slow-release source of nutrients for plants.

pH level: The pH level of soil affects the availability of nutrients to plants. Fertile soil usually has a pH level that is suitable for optimal nutrient uptake by plants. Different plants have different pH requirements, and maintaining the appropriate pH level is important for soil fertility.

Soil structure and texture: Fertile soil has good structure and appropriate texture, allowing for good water infiltration, drainage, and root penetration. Well-aggregated soil provides a suitable environment for plant roots, nutrient uptake, and soil organisms.

Biological activity: Soil fertility is influenced by a wide variety of active soil organisms, including worms, bacteria, fungus, and other helpful microbes. These organisms are crucial for the breakdown of organic materials, the cycling of nutrients, and the prevention of illness, all of which contribute to soil fertility.

Soil moisture and aeration: Fertile soil allows for the drainage of excess water while retaining sufficient hydration for plant development. This balance ensures that plants have access to water and oxygen for root development and optimal nutrient uptake.

Soil erosion prevention: Fertile soil has good structure and organic matter content, which helps prevent soil erosion caused by wind and water. Erosion can deplete topsoil, nutrients, and organic matter, negatively impacting soil fertility.

Sustainable management practices: Maintaining soil fertility involves implementing sustainable management practices, including crop rotation, cover cropping, organic amendments, and precision fertilization. These practices help replenish nutrients, improve soil structure, conserve soil moisture, and promote beneficial soil microorganisms.

Soil fertility is essential for sustainable agriculture, as it supports crop production, minimizes input requirements, and reduces environmental impacts. By implementing practices that promote soil fertility, farmers can optimize productivity, enhance soil health and resilience, and contribute to a more sustainable and productive agricultural system.

Factors that influence fertility in soil are Physical parameters like weather, soil composition, conductivity of electricity, and bulk density of the soil, water-retention proficiency. Chemical parameters include soil the pH level, capacity for cation exchange, and nutrients for plants (including macro and micronutrients). Biological parameters include soil mineral composition, biological material, microbes, and biogeochemical processes.

1.4 Role of Microorganisms in Topsoil Regeneration

Topsoil has many more microorganisms than subsurface because food supplies are numerous. They are especially plentiful in the rhizosphere, the region immediately next to the growing roots were sloughed off cells and substances generated by live roots provide available food sources. Soil microorganisms which include bacteria, fungus, viruses, protozoa, and archaea, conduct essential ecosystem tasks including degradation and nutrient cycling and develop symbiotic interactions with plants. N-deposition can affect the composition and purpose of microbial populations in soil in a variety of ways. Soil microbes are the most common biota in soil, driving nutrient and biological matter cycling, fertility of the soil, soil restoration, plant health, and ecosystem initial production. Beneficial microbes include those that form symbiotic relationships with the roots of plants (rhizobia, mycorrhizal fungi, and bacteria). Plant growth hormones (Biocontrol agents) produced inhibit the Plant parasitic organisms, illnesses, and pests. Although a number of these species already exist in the soil, it may be beneficial to expand their populations by implantation of other agronomic management techniques that increase their numbers and activity.

1.5 Importance of Minerals in Top Soil Regeneration

In the past few decades due to high chemical farming and many other human invasions the quality and nutrient content soil has been replenishing which in turn reduces nutritional values in food. Replenishing the minerals in topsoil plays an important role in improving the soil quality which in turn increases crop yield. Topsoil being the most important layer as majority of nutrients required for cultivation are present in the top layer of the soil. We can restore soil mineral content by maintaining consistent ground cover, increase microbial populations, stimulate biological variety, reduce agricultural chemical usage and prevent tillage. Every Plant require many nutrients to grow, nearly 17 nutrients are required for the plant in its life cycle out of 17 elements 14 are obtained from soil and rest are obtained from air and water which includes carbon, hydrogen and oxygen. Minerals with a percentage of between 40 and 45% make up the majority of the soil's constituents. The minerals in soil are divided into two groups, which are primary and secondary.

1.5.1 Primary Minerals

Primary minerals are those which are nearly identical to parental materials and not chemically changed since their deposition and usually larger in size. Most of the parental material is formed from sedimentary rocks hence the parental has major impact on the nutrient content of soil these minerals are formed high temperature by cooling of magma which includes feldspars, micas, and quartz.

1.5.2 Secondary Minerals

Secondary minerals are those which formed by weathering of primary minerals which usually make them smaller in size and mostly found in fine silt and clay they have ability to retain soil moisture. In contrast to primary minerals these are formed at low temperature reaction. Plant nutrient availability is controlled by secondary minerals due to its adsorption reaction [54].

Microminerals are often known as trace minerals which are needed in little quantities. As a result, they are occasionally referred to as minor minerals. Examples of trace minerals are the elements copper, iron, iodine, zinc, manganese, fluoride, cobalt, and selenium. Some of these important minerals required for plant growth and the function of minerals are given in a Table 2 [22].

As we have seen some nutrients and their uses for plants, now we got to know how important minerals for are plants to grow and also it is important to note that nearly 95% plants are grown on top layers of soil. Since many decades there is huge loss in top layer of soil and main cause of it is conventional farming which in turn affects the crop yield and the nutrient values of the crops [12].

Table 2 Different minerals and its functions

Name of the mineral	Function of mineral
Nitrogen	Proteins, nucleic acids, vitamins, and hormones all include nitrogen as the vital component. It is taken up as ammonium ions, nitrates, or nitrites. Meristematic tissues and metabolically active cells need nitrogen and its compounds
Phosphorous	Phosphorus is absorbed as phosphate ions and is found in cell membranes, proteins, and all nucleic acids and nucleotides. Energy obtained in photosynthesis is stored in the form of phosphate compounds (adenosine triphosphate) when plant requires energy it converts ATP to ADP a huge energy is released which is required for plant cellular activity
Potassium	Buds, leaves, and root tips are all tissues with meristematic properties that require potassium. It controls the anion-cation balance inside cells, participates in the production of proteins, opens and shuts pore spaces, keeps cells turgid, and contributes to osmotic pressure maintenance. Its absence may interfere the process of photosynthesis
Calcium	Calcium is essential for the production of mitotic spindles and the synthesis of middle lamellae. It is an important component for strength of cell membrane and permeability
Magnesium	Magnesium is a key component of chlorophyll and aids in the maintenance of ribosome structure
Sulphur	Sulphur is derived from the soil as sulphate ions. It is the primary component of several coenzymes, vitamins, and ferredoxin, it is essential component in plant protein
Iron	Compared to other micronutrients, iron is needed at higher concentrations. It comes from the soil as ferric ions. It functions as a key component of transport proteins, stimulates the catalase enzyme, and is necessary for the synthesis of chlorophyll
Manganese	Manganese activates numerous enzymes engaged in photosynthesis, respiration, and nitrogen metabolism. Its primary function in photosynthesis is the splitting of water
Molybdenum	Nitrogenase and nitrate reductase are two nitrogen metabolism-related enzymes that contain molybdenum as a key component
Chlorine	Chlorine aids in the determination of cell solute constituents and the maintenance of anion-cation equilibrium. It is crucial in the water splitting process of photosynthesis

According to recent survey it is being stated that there is a drastic decline of minerals in vegetables and meat due to decrease of minerals in top layer of soil shown in a Table 3 [27].

This shows how important are minerals present in soil hence minerals play a crucial role in top soil regeneration and an important thing to be noted that replenishing the mineral content should done in the other organic or microbial level (as microbial flora play main role to mineral content of soil) rather than through chemicals which is an improper way of fixing the soil nutrient values.

Table 3 Comparison of mineral depletion percentage in vegetables and meat

Name of the mineral	Percentage of depletion in vegetables (%)	Percentage of depletion in meat (%)
Copper	76	24
Calcium	46	41
Iron	27	54
Magnesium	24	10
Potassium	16	16

1.6 Genetically Modified Microbes Used in Topsoil Regeneration

Due to the limitations of native microbes to adapt and efficiently degrade pollutants in new environments, genetically engineered microorganisms offer a better solution. These modified microbes can effectively remediate a wide range of contaminants that regular indigenous microbes cannot. Various molecular tools, such as biolistic transformation, electroporation, and molecular cloning, enable the creation of genetically modified organisms (GMOs) with enhanced degradation capabilities. By introducing new genes that have a high potential for degradation speed up the clean-up process. By expressing genes contained in bacterial plasmids, engineered microorganisms may successfully repair substances including toluene, octane, naphthalene, salicylate, and xylene. The strategies comprise changing gene and metabolic pathways, establishing and managing bioremediation processes, and employing sensor-based biosorption reporters to detect contaminants, minimize exposure, and clean up the environment. Diminish toxicity, and predict the remediation outcomes [61]. Removal of heavy metals, even while some heavy metals may benefit living things, it is harmful for them to build up to dangerous amounts in the body. Humans who are exposed to toxic metals at high amounts over time may have a range of symptoms, including cancer, liver failure, brain damage, and even death. Heavy metals have also been connected in recent research to autoimmune disorders and birth abnormalities [23, 43]. While heavy metals are naturally found in the crust of the Earth, excessive amounts have been discharged into the environment as a result of industrialisation. [64] Genetically modified microbes designed for heavy metal removal utilize diverse approaches. These include modifying transport proteins responsible for metal transfer across microbial membranes and expressing a variety of metal binding protein molecules, such as phytoalexins, polyphosphates, ferritin, and metallothionein. Within the microbial cytoplasm, these metal-binding proteins serve as proteins that store for metals [16]. Examples: Escherichia coli will degrade the Uranium and chromium [53]. Posticous japonicus will degrade the metals like Cd^{2+}, Hg^{2+} and Cr^{3+}.

Pesticide degradation: Numerous genes exhibiting strong pesticide degradation capabilities have been identified, opening up opportunities for creating genetically modified organisms (GMOs) tailored to pesticide degradation. With the shift Biological pesticides are now a crucial part of sustainable agricultural operations as we move toward organic agriculture and the use of genetically modified plants for increased production. In soil, the designed bacteria are essential. Restoration by effectively breaking down persistent pesticide residues that would otherwise remain in the soil for prolonged periods. The dangerous herbicide atrazine, which is extensively used but poses threats to other creatures, was degraded using the gene atzA, which is responsible for manufacturing Atrazine chloro hydrolase. An engineered *Escherichia coli* with atrazine chloro hydrolase was shown to be able to treat atrazine-contaminated soil through field-scale investigations [56].

Hydrocarbon removal: Due to transportation mishaps, oil pollution has become a serious global hazard that affects inland water, soil, and marine habitats. The intensity of the oil spill and the exposure to other species determine the amount and toxicity of the pollution. Effective cleaning methods are required because of the consequent harm to the soil and plants. Given that several native strains have been discovered to be capable of hydrocarbon breakdown, biological techniques have benefits in terms of soil stability and effective restoration. Due to the complicated hydrocarbon composition of oil, genetically engineered microbes are, nevertheless, more effective at cleaning up oil-contaminated locations. To do this, superbugs can be produced by introducing plasmids harbouring several genes with deteriorating enzymes. For example, a reporter lux gene was added to an engineered strain of *Acinetobacter baumannii* S30 pJES with an excellent capacity for the degradation of total petroleum hydrocarbons (TPH), which was produced to monitor the bioremediation site [52].

2 Interrelation of Bio-sequestration with Topsoil Regeneration

2.1 How Carbon Sequestration Works?

Sequestering the gases carbon dioxide (CO_2) through the environment is a procedure that is primarily used to combat climate change and lower greenhouse gas emissions. This procedure uses a variety of organic and man-made methods to take carbon dioxide out of the environment and store it in various reservoirs for a long time. Geological, biological, and technological sequestration are the three basic categories.

2.1.1 Biological Carbon Sequestration

The utilization of trees, plants, and other living things for the absorption and storage of carbon dioxide through the processes of photosynthesis is known as “biological carbon sequestration”. Plants take in atmospheric carbon dioxide from the atmosphere during photosynthesis and transform it into organic materials like sugars and cellulose while releasing oxygen. The tissues of the plant, including the roots, stems, and leaves, then store the organic material. Agricultural areas, wetlands, grasslands, and forests are a few types of ecosystems that help in sequestering carbon [44].

2.1.2 Geological Carbon Sequestration

Geologic sequestration of carbon entails capturing and injecting carbon dioxide into subterranean geological formations. This technique stops CO_2 from entering into the atmosphere and instead retains it in permeable rock formations, including deep saline aquifers or depleted oil and gas reserves. These geological features trap CO_2 over time, diminishing its ability to make a difference to climate change. To avoid leaks and guarantee the stability of the carbon dioxide that has been stored, this method necessitates careful choice of location and monitoring [14].

2.1.3 Technological Carbon Sequestration

Technological carbon sequestration includes removing carbon dioxide emissions from power stations or industrial operations and storing or using the removed CO_2. There are several techniques for capturing CO_2, including oxy-fuel combustion, pre-combustion capture, and post-combustion capture. Once it has been caught, CO_2 can be moved to geological storage locations or, in certain circumstances, utilized for improved oil recovery (EOR), in which case it is introduced into reservoirs that hold oil to boost oil output [62]. It's important to note that while carbon sequestration technologies have the potential to play a role in mitigating climate change, they are not a standalone solution. Efforts to reduce greenhouse gas emissions at their source through energy efficiency, transitioning to renewable energy sources, and sustainable land management are equally important. Additionally, there are challenges associated with carbon sequestration, such as ensuring the long-term stability of stored CO_2, preventing leakage, and addressing potential environmental and social impacts.

Overall, carbon sequestration, in combination with other climate mitigation strategies, can contribute to lessening the effects of warming temperatures and lowering the atmospheric carbon dioxide concentration (Fig. 1).

2.2 Artificial Bio Sequestration

Artificial carbon sequestration refers to a variety of technologies that absorb and bury carbon emissions at the place of production (e.g., factory chimneys). Ocean sequestration is one suggested approach in which carbon dioxide is pumped deep into the ocean, generating CO_2 lakes. The CO_2 will, stay deep owing to the pressure and warmth of the adjacent water, eventually dissolving into it over time. Artificial Carbon Sequestration Potentiality quicker Sequestration, Natural sequestration takes longer

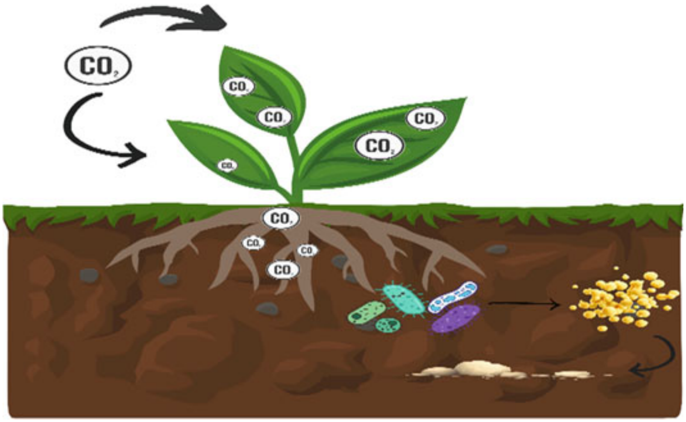

Fig. 1 Carbon sequestration

than artificial sequestration. As a result, it can supplement natural sequestration to accomplish the targets required to combat climate change. This results in increased agricultural production and improved oil recovery due to carbon trapped in subsurface chambers such as ancient oil reservoirs, aquifers, and coal seams.

2.3 Biologic Carbon Sequestration on Land

Biological carbon sequestration (also known as bio-sequestration) is the collection and storage Carbon dioxide, which is a gas that causes climate change, is present in the atmosphere. Through continuous or accelerated biological processes. This type of carbon sequestration happens as a result of enhanced photosynthesis rates caused by land-use techniques like as reforestation and conserving forests [9]. Land-use adjustments that improve natural carbon store have the capacity to absorb and store huge volumes of CO_2. Preservation, administration, and regeneration of habitats such as vegetation, peat lands, wetlands, and grasslands, as well as carbon sequestration strategies that includes agriculture [26].

The term “biological carbon sequestration” refers to the innate ability that allows individuals and surroundings to accumulate carbon. The coast’s forests, peat bogs, and wetlands regions are excellent carbon sinks. Carbon may be stored in plant tissue such as tree bark that is durable or extensive root systems.

Solutions for reducing organic carbon on land are seen as an important and useful way to bring about climate stability. Mitigation strategies must be driven by ecologically responsible and adaptive land management to fulfills the rising demands for food, energy-based products, wood, and biodiversity conservation, all of these compete for dwindling supplies of biomass and land. If properly implemented, organic carbon and biofuel mitigation strategies could prevent up to 38 billion tonnes of atmospheric carbon emissions and 3–8% of global electrical consumption by 2050, respectively. Compared to plants and the ecosystem as a whole, soils contain more carbon. (UNCCD) Carbon capture in agriculture has the potential to considerably lessen the consequences of global warming. Efforts to increase soil carbon retention will enhance soil quality concurrently. Carbon is a component of soil organic matter (SOM). SOM is a complex mixture of carbon molecules made up of carbon bonded to soil minerals, carbon from protozoa, nematodes, fungi, and decomposing plant and animal tissue. Low-till and no-till farming are examples of conservation tillage, which minimizes or completely avoids soil disturbance for crop production. One example is mulch tillage, which retains crop residue on the soil's surface. These methods generally reduce soil erosion, improve water efficiency, and increase topsoil carbon concentrations. Conservation tillage can reduce the amount of fossil fuels used in agricultural operations.

Cover cropping, the practice of using crops like clover and tiny grains to protect and improve soil between seasons of regular crop production. By enhancing soil structure and adding organic matter, cover crops boost carbon sequestration. Crop rotation—growing various crops in alternating years (e.g., corn-oats-clover) reduces carbon loss from the soil [3]. Grasslands add organic matter to the soil, mostly through their enormous fibrous root mats. Since the 1850s, a considerable fraction of the world's grasslands have been ploughed and turned to croplands, allowing enormous amounts of soil organic carbon to be rapidly oxidized. Livestock farmers may increase the retention of carbon on their farms by switching from continuous to rotational grazing. This maintains the plants actively growing and increases photosynthesis rates. This enhances the fodder quality and helps the plants to store more carbon.

2.4 Sources of Carbon Emissions

The global energy-related CO_2 emissions in 2022 grew by 0.9%, or 321 Mt, setting a new high of in excess of 36.7 Gt. As a result of COVID-19 reducing energy demand, growth in 2018 was substantially slower than the recovery of over six percent in 2021. While industrial processes lowered the amount they released by 102 million tonnes, pollutants from energy combustion climbed by 423 million tonnes. Despite several nations transitioning from gas to coal, global emissions increase was less than anticipated. Thanks to increased use of sustainable energy technology including renewables, electric cars, and heat pumps, in excess of 550 Mt of emissions of carbon dioxide have been averted.

This rise in emissions is the result of unique difficulties in 2022. 60% of the 321 million metric tons rise in CO_2 might be linked to the need for heating and cooling during severe weather conditions, and additional 55 million tonnes could be related to the shutdown of nuclear power plants. In 2022 emissions from the emerging market and developing economies of Asia, excluding China, are on track to exceed all other regions. This will increase CO_2 by 4.2% or 206 metric tons. Coal power plants accounted for more than half of the region's increased emissions [25].

Constructed wetlands: The balance of the world’s waters is affected by nature and built wetlands. The most important greenhouse gases, CO_2 and CH_4. They are important sources of CO_2 released by means of photosynthesis absorption sequester of organic substances created in the environment from the earth’s atmosphere, wetlands soil. In these systems the organic carbon is removed by the volatilization. The gases are removed either by diffusion of water or by active transport through the culms of wetland plant. Because of presence of convective flow mechanism in wetland plants, they release gases from the plant roots hence causing the high emissions of carbon in soil.

The presence of plant roots supports a variety of heterotrophic microbial processes. Hydrotropic potentials for wetlands soils with a complete, dissolved and microbial C has correlation as root exudates may form up to 20% of a plant’s annual above ground production. Root exudates are highly decomposable making easy for the microbial metabolism, resulting in huge carbon emissions in soil [50].

Fossil fuels: Since combustion of fossil fuels emits the carbons. They are coal, brown coal, peat and crude oil. The rise in carbon in atmosphere has increased rapidly accordingly from year 1751 to 1995 report produced through Oak Ridge National Laboratory’s Carbon Dioxide Information Centre [4].

Agriculture: About 20% of the world’s annual CO_2 emissions can be attributed to land use, changes in soil cover and agricultural practices. Agricultural practices may be used with regard to C emissions Primary, Secondary and Topiary Sources shall be grouped together (Fig. 2).

Tillage, seeding, harvesting, and transportation are the main sources of carbon dioxide emissions. Fertilizer and pesticide production, packaging, and storage are secondary sources of carbon emissions. Acquisition of raw materials, creation of machinery, and construction of agricultural structures are tertiary sources of carbon emissions [29].

2.5 Most Important Carbon Sinks

Before knowing the important carbon sinks, let’s understand what a carbon sink is. Carbon sinks are those which absorb the atmosphere carbon, these are nature’s way of reducing the emitted atmospheric carbon. This can be natural (includes oceans and forest) and artificial (includes chemicals or some techniques) they reduce atmospheric carbon. The process by which carbon sinks absorb the carbon dioxide from atmosphere is carbon sequestration.

There are three major natural carbon sinks: Ocean, Forest, Soil.

The carbon is exchanged between the source and the sink through a cycle known as carbon cycle. There are certain steps included in the carbon cycle; primarily the atmospheric carbon is observed by the plants by photosynthesis and that accumulated carbon taken in by many animals by consuming the plants and carbon get accumulated in them and the animals when die they get decomposed by microbes and CO_2 is

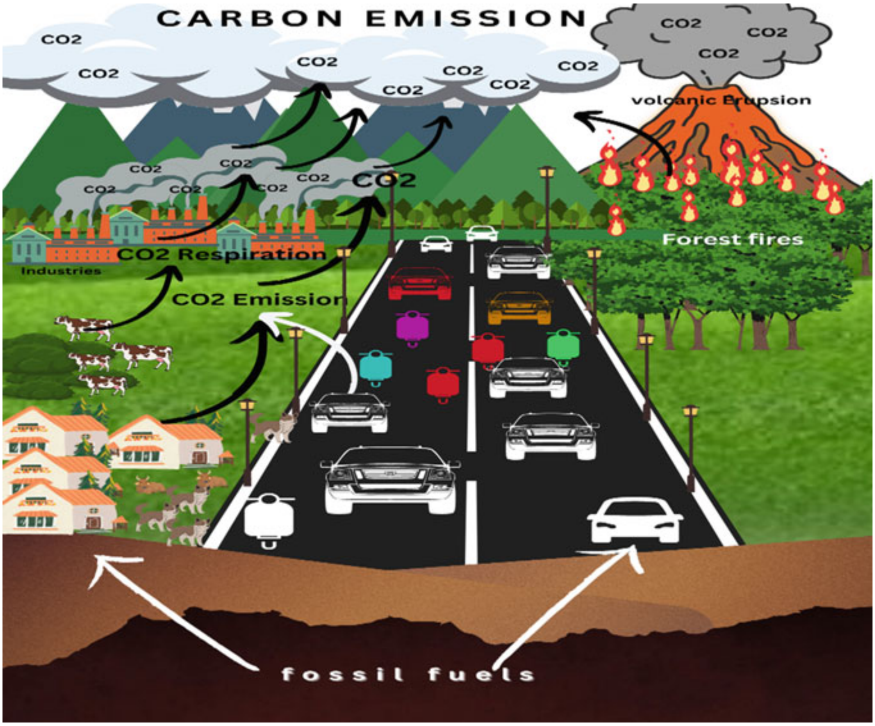

Fig. 2 Carbon emissions from different sources

emitted back to atmosphere the rest carbon is converted to fossil fuel and when they are burnt the carbon dioxide is released again into atmosphere [11].

2.5.1 Ocean as a Carbon Sink

Due to its vast spread it is the largest carbon sink, the majority of carbon dioxide which is emitted into the atmosphere by various human activities is absorbed by the ocean and stored in Deep layers of sink: They can act as carbon sink by a mechanism known as carbon pump. The biological carbon pump is the mechanism through which the atmospheric carbon is absorbed by ocean stored in its deep layers. Phytoplankton in ocean plays major role in carbon sequestration of ocean they absorb the dissolved carbon dioxide in upper layers of the ocean and also absorb the other elements and by photosynthesis it takes it up it also takes up the CO_2 formed in ocean by animal respiration/decomposition when the phytoplankton's die, they get sediment in deep layers of ocean this how the ocean sequent the atmospheric carbon [6].

Due to increased global warming which increases the temperature of ocean upper layers which is becoming threat for the life of phytoplankton's which can lower the ocean ability to sequent the atmospheric carbon and due to increase CO_2 levels and increased uptake by ocean which can alter the ocean pH which threatens the marine life known as ocean acidification [59].

2.5.2 Forest as Carbon Sink

With increasing human activities, the emission of carbon is increasing proportionally, which now makes people look for a carbon sequester. Forest with a large cover area act as a big carbon sink.

Recent studies on forest carbon emission through satellite study it is known that forests absorb double the amount of carbon than they emit which means forests absorb tons of carbon from the atmosphere every year [21]. Trees are the main carbon sinks in the forest; they absorb the atmospheric carbon dioxide and in the presence of light they form the sugar molecules they store that in them this is how the forest can work as carbon sinks.

The trunks of large trees can act as a big storage of carbon even trees also emits the carbon to atmosphere by breaking of sugars or by decomposing of leaves litter or dead trees but it can be neglected as decaying of big logs of tree take a long time even after they dead they can act as a carbon sink the young forest as they are growing fast they can absorb more carbon then the old forest but even though studies show the old forest are great carbon sinks as big trees has large amount of carbon stored in them then the young trees which makes them a large carbon sinks [35].

We can increase forest carbon sequestration by performing certain activities like forest management, afforestation and reducing deforestation. Afforestation involves changing abundant lands into forest which in turn increase the carbon absorption. Reducing deforestation and managing the forest can prevent the complete loss of forest area which leads to a huge decline in carbon sequestration [39].

2.5.3 Soil as a Carbon Sink

Both a source of carbon and a storage facility for carbon may be found in soil. A healthy soil can be a part of carbon cycle in which the litter and dead animals after decomposition the rest carbon is get under the soil where they are stored and the fossil fuel under the soil is a large carbon sink. Due to the many human activities and increased machinery which can take out the fossil fuel (there combustion release carbon) and increased deforestation and overgrazing leads to soil erosion which make soil less fertile to grow the plants all these activities can make soil form a carbon sink to a carbon source [28].

The natural carbon sequestration capability of soil is primarily due to plants which pull the atmospheric carbon through photosynthesis when they are alive and even after death it decomposes very slowly so it can store carbon for a long time. Even in some arid regions still soil can act as carbon sink by storing atmospheric carbon in inorganic form as secondary carbonate but its quantity is low natural store capacity

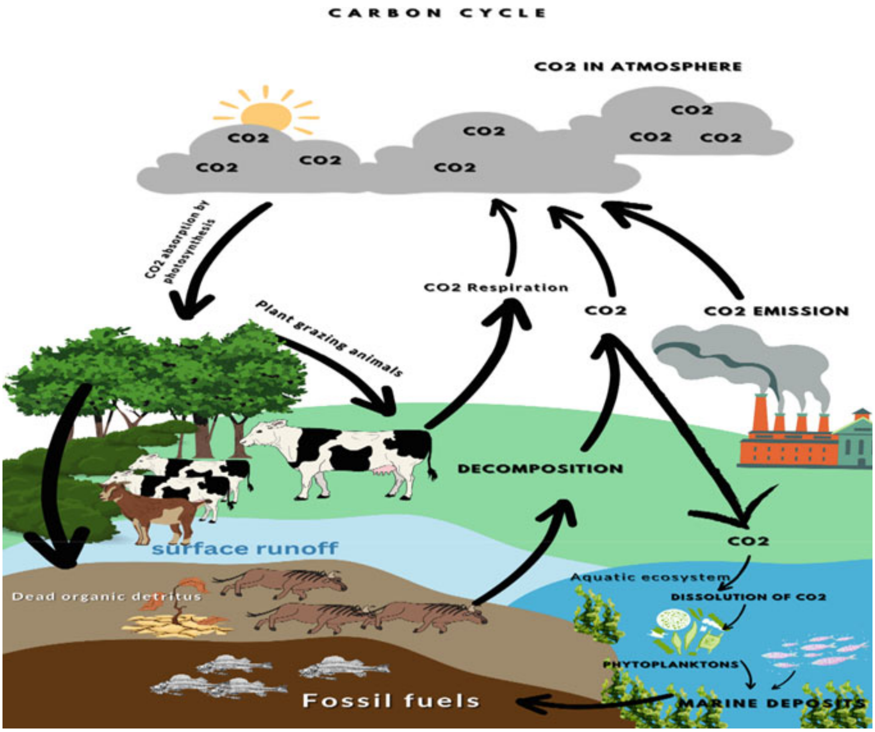

Fig. 3 Carbon cycle showing different emissions

of soil as carbon sequester can be obtained by reducing the soil erosion increasing soil quality by adding organic matter [46].

The practices to increase soil carbon sequestration includes both conventional methods and frontier technologies. The conventional method those which are known but not highly in use or in use by only some farmers which includes improved crop rotation management, adding compost, grazing management, etc. Currently the frontier technologies require more research and development they may be possible in upcoming years which can potentially increase soil carbon sequestration [49] (Fig. 3).

2.6 *Soil Organic Carbon*

Through photosynthesis, plants store carbon in the soil, which can then be deposited as organic matter in the soil (SOC). Despite the fact that agro ecosystems can degrade and cause SOC levels to drop, the carbon shortage offers the chance of storing carbon through cutting-edge land management techniques. Additionally, carbonates can be kept in soil. When carbon dioxide interacts with water and percolates into the soil over thousands of years, it combines with calcium and magnesium minerals to form “caliche” in dry, desert soil. Unlike soil organic matter, which can only store carbon for a few decades, carbonate minerals are mechanical and can store the gas for over 70,000 years. Scientists are investigating ways to accelerate the carbonates production procedure by introducing roughly broken minerals with silicates to the ground in order to retain carbon for a longer period of time. Carbon may be kept in storage for a longer period.

Soil organic matter is made up of measurable components like organic carbon. Even though organic matter makes up just 2–10% of the majority of soils, it plays a significant part in the physical, chemical, and biological processes that take place in agricultural soils.

Organic matter supports soil structure, moisture availability and retention, pollutant breakdown, carbon sequestration, and nutrient retention and turnover. By reducing atmospheric CO_2, the storage of carbon in SOC is being suggested as one strategy to combat climate change. According to the idea, little improvements in SOC over incredibly large used for agriculture and pastoral lands will considerably reduce atmospheric carbon dioxide. For the decline to be long-lasting, organic components have to exist in the more resilient or stable fractions. The supply of nutrients, water retention, soil drainage, the latter of stability of the soil, and emissions of greenhouse gases are all governed by soil organic carbon, which may either mitigate or worsen the effects of change in climatic condition.

2.6.1 Effects of SOC in Top Soil Regeneration

Soil organic carbon (SOC) can help increase crop yields, improve soil fertility, and reduce greenhouse gas emissions by acting as potential carbon sinks and improving soil structure and water storage [18]. Low levels of SOC are produced by the soil’s inability to retain nutrients and may result in lower yields of crops, decreasing soil fertility and triggering nutrient loss [8]. According to one study, increasing SOC in the top soil layer (0–20 cm) can result in greater yields of grains of 430 kg per hectare and a 3.5% reduction in crop instability [37]. Other research, however, concluded that the capacity to enhance SOC is frequently changeable, depending on climate conditions and Soil kinds. As a result, it is critical to understand the connections between carbon intake, SOC formation, and crop yields [47].

Photosynthesis and Greenhouse gases are the two key elements influencing bio-sequestration in the upper soil renewal. Photosynthesis removes CO_2 from the atmosphere as a plant grows. Soil Organic matter (SOM) gets returned to the soil as fungal and bacterial microorganisms, decomposing animal and plant tissue, and chemical compounds generated during decomposition. The organic carbon (SOC) stock of the soil is made up of these basins of C-rich elements. Some SOC oxidizes and gets released back into the atmosphere through respiration, particularly whenever topsoil is disturbed [30]. The capacity of the soil to store SOC is determined by specific environmental and climatological variables, land use, and physical soil qualities [34].

Greenhouse Gases (GHGs): The three main greenhouse gases that are produced are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Combined pollutants of greenhouse gases are frequently stated in the amount of carbon dioxide comparable or CO_2. This unit equalizes all emissions of greenhouse gases by describing them in relation to the volume of carbon dioxide required to produce the same climate change effect. Carbon dioxide alone accounts for more than two-thirds of total emissions. Nearly one trillion metric tonnes of emissions of carbon are currently trapped in the atmosphere, resulting in a carbon dioxide level of 407 ppm in 2018, which is 47% higher than pre-industrial levels. Soil carbon sequestration is focused on removing CO_2 from the environment, although regenerative farming techniques also lower CO_2, nitrous oxide, and methane emissions.

3 Quality Methods to Identify Soil Quality

3.1 RothamSted Carbon Model

The complex dynamics of carbon in terrestrial ecosystems are best understood using the Rothamsted Model of Carbon C, which was created at Rothamsted Research in the United Kingdom. Our understanding of carbon cycling, which is essential for tackling global climate change and maintaining ecosystem health, has significantly advanced thanks to our model. Since decades, there has been developing concern about a rise of the amounts of carbon dioxide (CO_2) in the atmosphere and their potential effects on climate change. The Rothamsted Model of Carbon C was developed by researchers at Rothamsted Research in the later part of the twentieth century as a solution to the difficulties. The objective of this creative initiative was to unravel the convoluted pathways of carbon transport across ecosystem components like vegetation, soils, and the atmosphere. The urgent need to understand the mechanisms underlying carbon dynamics, a necessary step in developing effective mitigation methods for the effects of global climate change, served as the impetus for the model's development [57].

3.1.1 Model Framework

The Rothamsted Model of Carbon C is a complex framework constructed from interconnected parts, built upon the foundation of systems ecology. This model deftly depicts the routes taken by carbon, which meander through organic matter reservoirs in the soil, vegetation, and litter while linking above and below ground systems. By taking into consideration the rates of uptake release and storage of carbon it skilfully portrays the dynamic interplay of carbon. But this model goes beyond the present, taking important environmental clues into account. Its computations use the dynamics of temperature, precipitation, and land use to control the flow of carbon. These elements like maestros conduct the symphony of carbon C influencing our comprehension of its complex dance within ecosystems and its function in the field of global climate change [51]. Vegetation Dynamics is recreating the development, aging, and demise of plants. It takes into account variables including photosynthetic rates, respiration, and carbon allocation patterns in various plant compartments. Litter Decomposition defines as the organic material such as plant litter which makes a major contribution to soil carbon. The model takes into account the effects of soil and climate on decomposition rates as well as the activities of microbes and decomposer species. The Rothamsted Model measures carbon transport between various soil carbon pools such as active slow and passive carbon fractions. It takes into account processes like as root turnover, microbial activity, and carbon stabilization mechanism. Conversion of land for agricultural, forestry, or urban purposes can have a significant impact on carbon cycling. This model integrates land use change scenarios to estimate how changes in land cover may affect carbon dynamics. Climate Inputs like temperature and precipitation for example, have a substantial impact on the speeds of carbon processes. This model incorporates the climate variables to simulate carbon C responses under various situations [38].

3.1.2 Applications

The Rothamsted Model of Carbon C has far-reaching implications for both research and policy formulation. The consequences of this model cut across disciplines elucidating the possible impact of land use decisions on carbon stores and directing the development of sustainable land management techniques. Furthermore, it has an impact on global carbon c models, where it plays a critical role in increasing understanding. The model improves our understanding in the prospective reactions in ecosystems by the onslaught of change in climatic condition by putting light on the complicated interplay between carbon dynamics and climatic variations. It serves as a compass in a sea of uncertainty allowing scientists, policymakers and stakeholders to navigate toward decisions that balance ecological integrity and planetary well-being [63].

Finally, the Rothamsted Model of Carbon C is an important tool for understanding the intricate web of carbon interactions within terrestrial ecosystems. It's multifaceted approach which includes plants, litter, soil and climate elements has shed light on the intricacies of carbon cycles and their impact in global climate change. As researchers work to improve and expand the model its findings will continue to guide our efforts to combat climate change and promote sustainable ecosystem management.

3.2 Uses of Soil Regeneration

The procedure of restoring soil is known as soil restoration by its health and fertility through various practices such as organic farming, crop rotation, cover cropping, and composting. This regeneration has several positive effects on the environment, agriculture and overall ecosystems. The outcomes of restoration of soil is given below: Improving soil fertility by enhancing organic matter and nutrient availability, soil regeneration can greatly improve soil fertility. This can lead to increased crop productivity and yield. Increased water retention which helps regenerated soil to have better water-holding capacity, allowing it to retain moisture for longer periods. This helps mitigate the effects of drought and reduces water runoff and erosion. Healthy soils support a diverse range of organisms such as earthworms, beneficial bacteria, fungi, and other microorganisms. Soil regeneration practices promote the proliferation of these beneficial organisms, which improves soil health and boosts overall biodiversity.

Regenerated soil has a better structure and increased organic matter content, which helps prevent soil erosion. This is particularly important in areas prone to heavy rainfall or steep slopes, where erosion can result in nutrient loss and land degradation. Soil regeneration techniques encourage the soil's ability to store carbon dioxide. Decomposing organic material, such as compost and plant remnants, releases carbon, which the soil subsequently absorbs and stores. By lowering greenhouse gas emissions, this helps to combat climate change.

Soil regeneration practices help restore soil structure, making it more resilient to compaction. This leads to better root penetration, nutrient absorption, and water infiltration. Overall, soil regeneration has a range of positive effects on the environment, agriculture, and sustainability. By promoting soil health and fertility, it contributes to food security, the preservation of ecosystems, the reduction of the effects of climate change, and environmentally friendly land management.

3.3 Virtuous Consequences

To increase the crop yield artificially farmer is adopting high use of chemical fertilisers which results in soil damage. Soil quality testing is considerably a best tool to understand soil nutrient content it physical and chemical nature. Through soil testing we can get a complete information regarding the nutrition values of soil which will help the farmer to understand soil nature and minimise the use of chemical fertilizers. By soil testing farmer can select right fertilisers and its required quantity for soil. Farmer can reduce the fertiliser usage that decrease the input cost and increase profit to the farmer. The right usage of fertilisers increases the soil health which leads to high crop yield [48]. Excessive use of fertilizers can lead to soil degradation this on long run can affect the crop yield. By testing the soil quality farmer can decide the fertilizer that need to use for particular crop in particular amount, which intern prevents the soil degradation and enhances the soil quality and soil health. The provision of micronutrients by the soil is essential for facilitating optimal plant growth and the synthesis of animal food. However, the quantity and accessibility of soil micronutrients has decreased as a result of the introduction of high yielding cultivars, intense cropping, decreased usage of organic matter, and a shift to high analysis NPK fertilizers [58].

For prevention of pollution soil testing plays a critical role in identifying and evaluating soil contamination caused by diverse pollutants such as heavy metals, pesticides, industrial chemicals, and hazardous substances. This data is vital for comprehending the scope of soil pollution and devising efficient remediation plans to safeguard human health and ecosystems. Furthermore, soil testing contributes to sustainable land management by offering valuable insights into soil fertility, nutrient levels, and organic matter content [17]. This information enables the adoption of precise and effective agricultural practices leading to reduced fertilizer usage and minimized nutrient runoff into water bodies. Soil testing results in decreased utilization of chemical fertilizers and this relationship is linked to landscape characteristics and farm intensity. This highlights the necessity for implementing targeted management approaches in making decisions at the farm level [42].

Assessing soil vitality Apart from nutrient levels, soil testing offers valuable information on essential soil properties like organic matter content, soil structure, and microbial activity. This data is instrumental in evaluating the overall health and fertility of the soil, promoting long-term soil conservation, and facilitating sustainable land management practices [60]. pH adjustments help Soil testing performances a vital function in determining the soil's pH level, by the critical for assessing its acidity or alkalinity. Maintaining the proper pH levels is essential for ensuring the availability of nutrients to plants. Imbalances in pH, whether too high or too low, can impede nutrient uptake and impact plant growth. With the information from soil testing, farmers can accurately apply pH-adjusting substances like lime or sulphur to establish an optimal growing environment for plants. The pH of the soil has a direct impact on the availability of vital nutrients. For instance, as the pH rises over 6.5, molybdenum and phosphorus become more accessible whereas iron, manganese, and zinc become harder to find. On the other hand, acidic soil enhances the solubility of minerals like zinc, aluminium, manganese, copper, and cobalt, making them more easily absorbed by plants. However, an excessive presence of these ions can be harmful to plant health. In alkaline soil, the abundance of bicarbonate ions disrupts the normal uptake of other ions, leading to adverse effects on plant growth [20].

For enhanced crop productivity in Soil the testing enables farmers and gardeners to gain insights into the soil's nutrient levels and pH balance. Armed with this knowledge, they can make well-informed choices regarding the suitable types and quantities of fertilizers and soil amendments required to maximize plant growth. As a result, crop yields are increased, and the quality of the produce is improved. Zinc is becoming second most deficient nutrient in soil next to nitrogen [5]. By analysing the nutrient levels in the soil, farmers can apply fertilizers more precisely, targeting areas with specific nutrient deficiencies and using right fertilizers, early detection. This avoids over-application of fertilizers in areas with sufficient nutrients, which can save on fertilizer costs. Soil testing can determine the best timing for fertilizer application. Applying fertilizers when the crops need them most improves nutrient uptake and reduces the need for repeated applications, cutting down on costs.

3.4 Other Following Methods

The soil quality affected by biota; the presence or absence of several organisms they include bacteria, fungi, algae, actinomycetes, protozoa, nematodes, earthworms and moles etc., [55]. The soil structure significantly impacts various soil characteristics, as it determines the presence of porous spaces between soil particles. These spaces facilitate water drainage, leading to either well-drained soils or surface water retention that can harm plants. Loose soil structures benefit plant growth by offering easy root penetration and allowing seeds to germinate. For farmers, this is a critical concern, as compacted soil from heavy rain can trap seeds below the surface, leading to failed sprouting. Moreover, the soil structure can influence soil colour, with loose soils enriched by plant life and decomposing matter appearing dark or black. Nutrient retention capacity of soil and Water-soluble nutrients migrate throughout the soil profile under the root zone of plants through a process known as leaching in which more water percolates through the soil than the soil can hold. This process, which results in acidic soil is typically made worse by significant rains [32]. Globally, there are 3.95 billion hectares of acidic terrain [45]. Nutrient retention of the soil is the ability of the soil to keep and supply vital nutrients to plants which is referred to as soil nutrient retention, and it depends on several elements like soil the pH level, the capacity for cation exchange (CEC), organic matter concentration, and clay minerals. Higher CEC and higher biological content soils tend to have better nutrient retention, ensuring that plants can access the vital elements needed for their growth and well-being. Sufficient nutrient retention in soil is vital for supporting agriculture and maintaining ecosystem health.

3.5 Improving Capacity of Topsoil Regeneration

Organisms in the soil significantly contribute to the enhancement of soil quality and the reduction of degradation risks, while soil biodiversity is essential for the proper functioning of ecosystems. The farming system of conservation agriculture is capable of preventing the loss of farmable land by advocating for minimal soil disturbance, the preservation of a permanent soil cover, and the diversification of plant species. The fundamental principles for enhancing soil quality in conservation agriculture include maintaining crop remnants, integrating a cover crop into the rotation cycle, utilizing integrated nutrient management (INM) which involves the combined use of chemical and biofertilizers, and avoiding soil mechanical disturbances. [31]. One can improve soil quality by following measures like:

Restoration of Physical Properties: Mitigating desertification, enhancing soil aggregation, increasing water permeability, expanding plant-accessible water capacity, advancing aeration.

Restoration of Chemical Attributes: Easing acidification, establishing a beneficial balance of elements, Amplifying the activity and capacity of nutrient reserve, Reducing sanitization.

Restoration of Biological Elements: Boosting microbial biomass carbon, fostering soil biodiversity, developing soils that suppress diseases, Augmenting populations of mycorrhizal and rhizobia organisms Ecological Restoration: Increasing the soil carbon pool, reinforcing elemental cycling, forming a balanced hydrological condition, Enhancing the services provided by the ecosystem. Sustainable intensification (SI), a method that increases productivity while minimizing resource usage by reducing waste and enhancing efficiency, can be achieved by enhancing the chemical composition and fertility of soil. An effective way to increase soil fertility is by applying Integrated Nutrient Management (INM) products. The main reasons for reduced productivity are nutrient depletion and declining soil fertility [24]. Utilizing organic additives, recycled organic by-products, and urban waste can serve as effective strategies to enhance soil fertility [1]. Improving soil structure to maintain the stability of soil aggregates is also important [2]. Nitrogen, though essential for soil fertility, can cause environmental pollution when used excessively. China, which consumes about 30% of global nitrogen fertilizer and contributes approximately 22% of the world's food, faces many environmental issues due to nitrogen runoff on reactive surfaces, impact on groundwater, and dangerous nitrogen emissions into the atmosphere. [33] One of the most serious consequences of soil degradation is the emission of greenhouse gases, such as CO_2 and CH_4.

Improving top soil regeneration capacity is done in several ways, some of them are listed Including livestock in Regenerative agriculture doesn't depend on animals, but when cattle graze, their manure enriches the soil with nutrients, providing a vital service. This process fosters soil health by promoting organic matter, boosting soil microbes, and improving nutrient cycling. In healthy soil, various natural organisms like earthworms, invertebrates, and fungi thrive, offering valuable contributions such as fertilization and aeration. Earthworm castings further enrich the soil with organic matter, nutrients, bacteria, and enzymes. To check for the presence of these organisms, perform random visual inspections of your garden soil. Minimizing the use of aggressive tillage might offer a temporary solution to soil issues caused by the absence anchored in living cover. But frequent or vigorous tillage increases the susceptibility to soil erosion. The soil's biological nitrogen and carbon are depleted, releasing nutrients quickly in the short term. But depleting them in the long term. This practice also harms beneficial soil-building organisms like mycorrhizal fungi and key invertebrates like earthworms. With excessive tillage and reduced photosynthetic capacity in bare soil, organic matter undergoes increased oxidation, releasing carbon dioxide into the atmosphere and potentially contributing to declining atmospheric oxygen levels. Embracing reduced or no-till practices in regenerative agriculture can yield various benefits for growers. These techniques can lead decreasing soil crusting, enhancing soil nutrient retention, increasing crop availability, increasing water absorption and retention, and gradually increasing soil organic matter. Crop productivity increases as a result of crops being more stress-resistant. By utilizing water more efficiently, using less fertilizer, and needing less soil tilling, producers may also cut expenditures. Overall, these low or no-till farming techniques are essential to regenerative agriculture, repairing soils and providing short- and long-term social benefits.

Regenerative agriculture decomposition concentrates on generating organic soil from natural materials like crop leftovers, food waste, and animal manure in order to replenish depleted soils. These substances include carbon, which slowly breaks down to generate stable organic matter over time, nourishing the soil. Composting accelerates the decomposition process, yielding goods made from compost that are easier for plants and soil microbes to utilise. This composting process is aided by earthworms, nematodes, bacteria, fungus, and several other organisms. Composts provide long-term advantages over conventional fertilizers since they replace carbon and decaying matter in addition to fertilizing the soil and crops. Crop productivity, soil quality, environmental safety, and human well-being are all impacted by soil deterioration, which presents substantial issues for farmers. Cover cropping of numerous crops can be used, depending on the location and the needs of the soil. Because they effectively scavenge excess nutrients still present in the soil following crop harvest, cover crops are very advantageous. The biomass of the cover crops contains these nutrients, making them sustainable for the next planting season. In addition, cover crops are quite important of decreasing farmland discharge and the essential spilling of fertilizers into river basins and underground water. Leguminous cover crops, in particular, help decrease the need for nitrogen fertilizers by fixing from surrounding environmental nitrogen to the soil.

Straw coverings can be seeded in between rows in systems with perennial crops, preserving soil coverage to prevent degeneration, control weed expansion, and offer environment for pollinators. Their usage is an essential approach to enhance soil biology and structure, recycles nutrients, reduces reliance on fertilizers with artificial components, sequesters environment carbon to the soil, it lessens farmland discharge. Which the essential equipment might promote overall productivity, rejuvenating soils for better crop health and higher yields. Photosynthesis is a natural process that removes a substantial amount of CO_2 from the atmosphere annually, amounting to hundreds of billions of tonnes. The transfer from atmospheric carbon to the soil, facilitated by growing plants, is significantly effective method which possess to restore the following soil function and decrease atmospheric CO_2 levels. Although all green plants serve as generated by photovoltaic energy pumps, it's rate and capability of the photosynthetic process in active plants, not their residual biomass, those play a key role in bio sequestration, leading to the accumulation of stable carbon in the soil.

Lessening soil interference involves preserving soil cover, plays a vital role in supporting and enhancing soil health. This approach aids in conserving soil moisture, boosting organic content, enhancing soil structure, and mitigating runoff and soil erosion. Soil protection can be achieved through two methods; indirect shielding, it involves leaving agricultural residue on the ground post-cropping, and dynamic shielding, that encompasses developing agricultural cover crops Forming soil interference comprises maintaining soil cover which is crucial for promoting and maintaining soil health. This practice helps retain soil moisture, increase organic matter, improve soil structure, and reduce both runoff and soil erosion. Soil armour comes in two forms i.e., Passive barrier defences that includes leaving waste from agriculture left over from harvest, as well as dynamic protection so, it entails developing agricultural cover crops. Active barrier which works on cultivating cover crops.

4 Principle Risks of Topsoil Regeneration and Bio Sequestration

It's important to keep in mind that any intervention in complex ecosystems may have unintended repercussions, even while bio-sequestration and topsoil restoration are commendable goals. Despite the potential benefits, such as improved soil fertility, higher water retention, and carbon storage, there is a dearth of knowledge regarding the probable hazards associated with these practises. It is crucial to carefully analyses any potential trade-offs, ecological disruptions, and unanticipated effects due to the complex interactions between soil ecosystems and their surrounds. The longevity and performance of programmes for topsoil regeneration and bio-sequestration depend on identifying and managing these risks in order to avoid unfavourable results.

The revolutionary strategies of topsoil regeneration and bio-sequestration have the power to change agricultural landscapes. Improved agricultural production can result from the regeneration of deteriorated topsoil, which can also improve soil structure, microbial diversity, and nutrient cycling. Similar to carbon sequestration, which involves capturing and storing carbon in soil organic matter, bio-sequestration can slow down climate change by lowering the atmospheric levels of carbon dioxide [13].

4.1 Risks

Soil Disturbance: The process of topsoil regeneration may momentarily disturb the microbial populations and soil structure, impacting capacity of vitamins and minerals together with operation of its ecosystem. Imbalances in soil nutrient availability can result from rapid changes in carbon and nutrient inputs, which could potentially have an impact on plant growth and productivity.

Gas Emissions: Although bio-sequestration tries to lower greenhouse gas concentrations, soil management's disturbance could result in immediate emissions.

Biodiversity Impacts: Changes in soil properties may have an impact on belowground biodiversity, which could alter ecosystem resilience and stability.

4.2 Methodology to Overcome Risks

Risk Identification: To identify potential dangers related to topsoil regeneration and bio-sequestration, conduct a thorough assessment of the scientific literature. Sort these dangers according to their ecological, agronomic, and environmental impacts.

Literature study: To comprehend the impacts of topsoil regeneration and bio-sequestration on soil characteristics, biodiversity, water quality, and greenhouse gas emissions, systematically study and analyse existing studies. In order to present a comprehensive picture of potential dangers and advantages, synthesise findings.

Quantitative Analysis: Use the data at hand to estimate and quantify potential risks, such as alterations in soil characteristics or emissions of greenhouse gases, under various topsoil regeneration and bio-sequestration scenarios.

Recommendations: Create guidelines for the implementation, administration, and oversight of topsoil regeneration and bio-sequestration practises that are based on scientific research for use by practitioners, decision-makers, and land managers. Discuss the risks that have been identified and offer plans for risk reduction and flexible management.

By methodically assessing the main dangers connected to topsoil regeneration and bio-sequestration technologies, the idea proposed herein aims to fill a significant research need. This research intends to offer stakeholders useful insights into the trade-offs and unintended repercussions of these practises by thoroughly identifying and analysing potential dangers. This study helps to develop sustainable strategies for topsoil management and carbon sequestration by illuminating the associated risks, benefits, and factors. By doing so, it ensures the long-term viability and efficacy of these strategies in addressing today's global challenges [15].

5 Educating/Giving Awareness Regarding Soil Restoration

Now a days it's been an important issue to be consider as educating or spreading awareness on soil restoration as do many human invasions by various ways (deforestation, industrialization, dumping hazardous chemicals waste etc.) destroying the soil which leading to the degradation of soil quality which in turn affect the soil health by disturbing the soil nutrients.

For considering as an example as we know most of our food nearly 90–95% of it is grows on top soil [36] due to destruction of these layer decreases the productivity and quality of the food we grow to compensate this loss of minerals to increase the productivity of cultivation it being heavily practised to use chemical fertilisers which might be increasing the productivity but it destroys the health of people who consume it.

Because of such heavy chemical farming people who consume have shown an increased metabolic disorder. The health conditions and the life expectancy have been decreasing by generation to generation. Due to such harmful way of cultivation it is being estimated that only 60% of topsoil is left on the earth.

It is known there are many ways of soil erosion (nearly 13 ways) which includes both environmental (wind erosion, water erosion, etc.) and industrial/human invasions (acidification, saltwater absorption, emissions, expansion, and physiological deterioration etc.) [41]. Even though soil disintegration is ecological phenomenon but while it is being enhanced by different human invasion and a step be taken to reduce it and there are many other procedures by which we can revive the soil health and improve the food production. Regenerative agriculture of the method by which we can reform the soil and maintain its quality in spite we can improve the soil quality. To bring the huge impact on soil there should be interlinking between the educators and people for an example in every village there should be frequent conduction of programs for educating the farmer in many beneficial ways of farming which will not only improve the production but they can maintain the soil quality naturally they should be trained to how to minimise the chemical fertilisers as less as possible and they should be given scientific knowledge of different method of cultivating in such easy method so that they can practise them.

Nowadays even the government has proposed many schemes on farming which would benefit agriculture and educate farmers on the various agriculture practices. Soil science is a vast subject there should be interlinking between the farmer, educators, industry on understanding and production Studies on soil science should be encouraged to students and there should be a new course on soil science so that the upcoming generation could have an knowledge on the soil science and it should be made a basic topic in the curriculum so that studying and understanding soil science and the benefits of soil restorations, major cause of soil damage [19].

Encouraging the soil science as undergraduate and graduate program with a well-defined curriculum with access in various areas of soil science will provide the students a very good approach on various aspects of soil science like soil morphology, soil chemistry, soil mineralogy which provide students a vast opportunity for students to pursue their career in various ago industries and provide a connection with the soil restoration [10].

Educating the soil science at various levels can increase the connectivity with soil to those who are not aware of soil science which could bring greater connectivity to soil. Educating should be through various routes such that non soil specialist can also get the knowledge of soil which will be great benefit we educate the non-soil specialties through various routes like social media, news channels various tv programs which in turn bring greater connectivity with soil.

There are many other modern methods like apps games which would attract the non-expert people and connect them with the soil by educating the present and upcoming generation about soil science/soil restoration would bring a major impact and reduce the soil destruction which would in turn help in soil restoration. Farmer as main producer they should be educated with various method to restore soil and prevent soil destruction they should be agriculture teaching programs to be conducted in every village by agriculture department and they should teach how to minimise the fertilisers and they should provide the native variants of seeds which would be capable to yield high with less consumption of chemical.

There should be encouragement in practising modern method including the traditional methods so that the yield could be increased along with the improving soil health usage of natural fertilisers like cow dung, neem oil etc., should be encouraged and they should be taught the value and benefits of organic farming. By spreading the soil knowledge to farmers, students and public we can achieve the improvement in soil health and prevent soil destruction and achieve soil restoration.

6 Conclusion

Soil regeneration is vital for long-term environmental sustainability, food security, and biodiversity conservation. Embracing sustainable agricultural practices and promoting soil health can have a positive impact on the environment and human well-being. climatic change mitigation measures, food security, climatic adaptability, the environment, and the condition of the soil are all interconnected, and regenerative agriculture has the potential to address all of them. Improve the tensile strength of the soil to minimize slide failure and raise the soil's carrying capacity; immobilize or stabilize pollutants in dredged soil to reduce, if not eliminate, environmental repercussions. The administration of the soil refers to a multitude of strategies used by landowners and agriculturalists to protect their most precious resource, soil resources. They reduce the loss of soil and increase the stability of the soil by using natural preservation methods, which include proper soil preparation. Carbon absorption and sequestration is an appealing alternative for lowering greenhouse gas emissions and may potentially assist in chemical elimination of the gas carbon dioxide in the environment. Gathering, eliminating, in addition to retention of atmospheric carbon dioxide (CO_2) from the environment is known as sequestration of carbon. It has become widely recognized as a major process for reducing CO_2 in the environment's surroundings.

7 Future Challenges

The positive effects of soil regeneration on the environment, agriculture, and ecosystems include:

Enhanced soil fertility: Rejuvenated soil becomes nutrient rich, fostering better plant growth and higher agricultural yields. This contributes to improved food security and supports sustainable farming methods.

Increased water retention: Regenerated soil exhibits better water-holding capacity, reducing runoff and erosion. It retains water during dry periods, making it more resilient to droughts and providing a stable water supply for plants and ecosystems.

Bio-sequestration: Soils that are healthy operate as a source of carbon, capturing atmospheric carbon dioxide as well as mitigating climate change. Soil regeneration practices like cover cropping and reduced tillage raise soil carbon content, helping offset greenhouse gas emissions.

Support for biodiversity: Healthy soils create habitats for beneficial microorganisms, insects, and other soil-dwelling organisms. Soil regeneration fosters biodiversity, leading to a more balanced and resilient ecosystem.

Improved soil structure: Soil regeneration enhances soil structure with improved aggregation and reduced compaction. This facilitates better root penetration and aeration, supporting healthier plant growth and reducing soil erosion risk.

Reduced dependence on synthetic inputs: By promoting soil health, the need for synthetic fertilizers and pesticides is minimized. This reduces costs for farmers and mitigates potential negative impacts on the environment and human health.

Restoration of degraded lands: Soil regeneration plays a key role in reclaiming abandoned agricultural fields or mining sites, transforming them into productive and sustainable areas.

Greater resilience to extreme weather events: Healthy soils better withstand extreme weather conditions, such as heavy rainfall or flooding, due to improved water infiltration and drainage capacity.

Improved water quality: Soil regeneration practices decrease the leaching of harmful chemicals and nutrients like nitrates and phosphates into water bodies, safeguarding water quality and aquatic ecosystems.

Economic benefits: Soil regeneration leads to higher crop yields and healthier agricultural systems, fostering increased economic stability for farmers and rural communities.

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Soil Erosion, Mineral Depletion and Regeneration

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Abstract Recent years have seen a rise in awareness of the urgent environmental issues of soil erosion and mineral depletion, which have far-reaching effects on agriculture, the health of ecosystems, and the encouragement of sustainable land use. This abstract seeks to provide a summary of these interrelated occurrences by looking at their underlying origins, effects, and potential solutions. Both global food security and environmental balance are seriously threatened by the interconnected processes of soil erosion and mineral depletion, which are both defined as the physical removal of the topsoil layer. To support plant development and preserve soil fertility, certain minerals and nutrients are crucial. When vital substances like nitrogen, phosphorus, potassium, and micronutrients are eroded or leached from the soil at a pace that is quicker than they can be naturally supplied, the result is mineral depletion, also known as soil nutrient depletion. This depletion is caused by intensive farming methods, uneven fertilization, and poor soil management. A limited and priceless resource, soil serves as the foundation for agriculture and the maintenance of a variety of ecosystems, maintaining life as we know it on Earth. However, the concurrent problems of mineral depletion, or the loss of vital nutrients from the soil, and soil erosion, which is the process by which soil is displaced or washed away by natural forces, represent linked risks to the sustainability and productivity of our landscapes. This abstract highlight the causes, effects, and potential solutions of mineral depletion and soil erosion from a basic perspective. Soil erosion is caused by a variety of sources, including both natural and man-made forces. Erosion rates are accelerated by human activities including deforestation, agriculture, building, and mining as well as by natural forces like precipitation, wind, and geological processes. Overgrazing and

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monoculture farming are only two examples of unsustainable land management practices that significantly contribute to erosion. There are several effects of soil erosion on both terrestrial and aquatic environments. It has an adverse impact on agriculture, lowering crop yields and raising expenses of production. Sediment flow from degraded soil can clog waterways and harm aquatic ecosystems and water quality. Furthermore, soil erosion increases susceptibility to climate change, the loss of arable land, and the deterioration of biodiversity. There is a complex relationship between soil erosion and mineral depletion. Mineral depletion is accelerated by the removal of key nutrients necessary for plant development by eroded topsoil. On the other hand, nutrient-depleted soils may have less plant present, making them more prone to erosion. The detrimental effects on ecosystem health and agricultural output are amplified by this feedback loop. As a result of crop nutrition being compromised by mineral depletion, human and animal diets become deficient. In addition to lowering food quality, it makes it harder for soils to support a variety of plant species and maintain ecological balance. The lack of some minerals, such as phosphate and potassium, also increases dependency on synthetic fertilizers, which have their own negative effects on the environment and the economy. It is necessary to employ a multimodal approach that includes sustainable land management techniques, regulatory interventions, and technical advancements to address the problems of soil erosion and mineral depletion. The use of precision agriculture, which uses technology to assess soil nutrient levels and apply fertilizers more effectively, soil testing, conservation agriculture, afforestation and reforestation, government policies that enforce regulations and provide incentives to encourage responsible land use, research, and education are important strategies. In order to protect both the resilience of ecosystems and global food security, soil erosion and mineral depletion are connected environmental concerns that must be addressed right away. For a sustainable future to be ensured, a complete understanding of the causes, effects, and potential remedies for these difficulties is essential. Policymakers, farmers, researchers, and the larger society must work together to combat soil erosion and mineral depletion in order to save our priceless soil resources and advance ethical land management techniques.

Keywords Erosion · Depletion · Soil and Environment

1 Introduction

Throughout history, soil has consistently held a pivotal significance in the sustenance and prosperity of the human species. Throughout human history, soil has been of paramount importance in facilitating agricultural productivity and sustaining a wide array of ecosystems, spanning from ancient civilizations to contemporary times. The escalation of soil erosion and mineral depletion has generated apprehension regarding the sustainable longevity of agricultural systems and the environmental well-being [1]. Soil erosion refers to the process of soil particles being displaced or moved by external forces such as wind or water [2]. The process of erosion, which has historically transpired as a natural phenomenon, has been expedited by human activities. Consequently, there is a significant annual loss of extensive tracts of cultivable land, leading to a decline in agricultural output and heightened susceptibility of the ecosystem to additional deterioration [3]. Soil erosion poses a dual threat to agricultural systems and environmental sustainability, as it can arise from both natural phenomena and anthropogenic activities [4]. The process of soil erosion is multifaceted and influenced by numerous variables. Various natural forces, such as wind, water, and gravity, contribute significantly to the transportation of soil particles. However, human activities, such as deforestation and inadequate land management practises, have been found to considerably intensify erosion rates [5]. These processes have the potential to disrupt the structure of soil, leading to a reduction in its capacity to retain water and a depletion of essential nutrients and minerals. Therefore, it can be inferred that soil erosion has extensive implications for agricultural and ecological systems [6].

Mineral depletion, conversely, pertains to the progressive diminishment of vital nutrients and minerals within the soil. The aforementioned nutrients are essential for the growth of plants and serve as a fundamental component in maintaining the nutritional value of crops. Soil erosion not only results in the depletion of fertile topsoil but also hastens the exhaustion of minerals, thereby compounding the difficulties experienced by farmers and ecosystems [7].

The ramifications of soil erosion transcend the immediate depletion of nutrient-rich topsoil. According to [8], soils that have undergone erosion undergo a decrease in nutrient availability, resulting in the depletion of minerals and imbalances that negatively impact plant growth and agricultural productivity. The erosion or leaching of essential minerals, such as nitrogen, phosphorus, potassium, and micronutrients, has detrimental effects on soil fertility and agricultural productivity. In addition, the process of sediment erosion has the potential to negatively impact the quality of water, thereby posing risks to both aquatic ecosystems and human well-being [9]. Gaining a comprehensive comprehension of the complex interplay b between soil erosion and mineral depletion is of utmost importance in formulating efficacious approaches to tackle these issues. Through a comprehensive understanding of the underlying factors contributing to erosion, including alterations in land use and inadequate agricultural methods, it becomes feasible to implement focused interventions aimed at mitigating the rates of erosion. The acknowledgment of the effects of erosion on the depletion of minerals allows for the development of suitable strategies to replenish vital nutrients and revive the fertility of soil [5].

2 Causes and Consequences of Soil Erosion

Soil erosion, a geological phenomenon characterised by the displacement or removal of soil due to natural forces, is subject to the influence of various factors. Soil erosion over extended periods of time has been attributed to various natural phenomena, including wind, water, and gravitational forces. Nevertheless, it is important to acknowledge that human activities have significantly expedited the pace at which soil erosion takes place [10].

The process of deforestation, as exemplified by the removal of trees, eliminates the shielding effect provided by these trees, which serves to stabilise the soil. Consequently, the absence of this protective cover renders the soil susceptible to erosion caused by wind and water [11]. Soil erosion can be exacerbated by inadequate land management practises, such as the utilisation of unsuitable tillage techniques or the practise of leaving fields uncultivated during intercropping periods. The process of overgrazing by livestock can result in the depletion of vegetation cover, thereby leaving the soil vulnerable to erosion-causing factors. In addition, the overutilization of synthetic fertilisers and pesticides has the potential to disrupt the composition and integrity of soil, thereby diminishing its capacity to withstand erosion [12].

Soil erosion engenders substantial consequences that exert extensive effects on both human and environmental systems. One notable outcome that is readily apparent is the diminished agricultural productivity [13]. The depletion of fertile topsoil, which is rich in essential nutrients and organic material, results in a decline in the capacity of plants to flourish and prosper. The aforementioned circumstance presents a significant peril to the worldwide sustenance stability, given the escalating difficulty in attaining sufficient agricultural yields to meet the demands of the expanding populace. The decrease in agricultural productivity can also have a significant impact on poverty and malnutrition, especially in areas where agriculture plays a crucial role in supporting people's livelihoods and providing sustenance [14]. Moreover, soil erosion has adverse environmental consequences. When soil erosion occurs, the resulting sediment runoff has the potential to enter water bodies, including rivers and lakes. The process of sedimentation has the potential to result in water pollution and hinder the overall quality of water, rendering it unfit for human consumption and causing disturbances in aquatic ecosystems. Excessive sedimentation can have detrimental effects on the habitats of aquatic plants and animals, resulting in a decline in biodiversity [15]. In addition, it is worth noting that soil erosion plays a significant role in the exacerbation of climate change through its contribution to the heightened release of greenhouse gases. Soil serves as a significant reservoir of carbon, and its erosion leads to the liberation of the carbon it harbours in the form of carbon dioxide, subsequently being emitted into the atmosphere. The emission of carbon dioxide plays a significant role in exacerbating the greenhouse effect, thereby contributing to the acceleration of global warming. The aforementioned phenomenon triggers a cascade of consequences related to climate change, including elevated temperatures, modified precipitation patterns, and heightened intensity of storms [16]. The process of soil erosion is a multifaceted phenomenon that has wide-ranging implications. The phenomenon in question is a significant factor in the occurrence of climate change, posing a substantial risk to agricultural productivity, food security, water quality, and biodiversity. In order to develop and implement effective soil conservation measures, it is imperative to identify and investigate the underlying causes of soil erosion. The mitigation of soil erosion is of utmost importance in order to minimise its detrimental impacts and safeguard the sustainable functioning of agricultural systems and the overall ecological well-being [17].

3 The Impact of Soil Erosion on Mineral Depletion

There exists a direct correlation between soil degradation and mineral depletion. The process of topsoil erosion results in the depletion of essential minerals, leading to a decrease in fertility and nutrient content of the remaining soil [18]. The phenomenon in question is primarily observed to have an impact within the A horizon, which represents the uppermost layer of soil where the accumulation of organic matter and minerals takes place. The depletion of this nutrient-rich layer has been found to diminish the soil's capacity to support robust plant growth and maintain sustainable productivity over an extended period [19]. The depletion of minerals in eroded soils has detrimental implications for agricultural practises. In order to achieve optimal growth and yield of nutrient-dense crops, it is essential for plants to have a well-balanced supply of both macro and micronutrients [20]. The depletion of minerals, particularly nitrogen, phosphorus, potassium, and calcium, leads to a scarcity of crops. According to Haider et al. [21], the aforementioned conditions result in impaired growth and development, reduced agricultural productivity, and heightened susceptibility to infections and pests. Furthermore, the depletion of minerals has a substantial impact on the nutritional composition of our meals. The consumption of plants cultivated in nutrient-depleted soils may lead to malnutrition and various health complications due to their inadequate composition of essential elements for human well-being. The maintenance of soil integrity and the restoration of essential nutrients are imperative for the sustained production of nutritious food and the enhancement of human well-being [22]. Various measures are being implemented to address the issues of soil erosion and mineral depletion, including the implementation of soil conservation techniques, the adoption of sustainable agricultural practises, and the utilisation of nutrient management strategies to restore depleted minerals [23]. According to Jose [24], the implementation of measures aimed at safeguarding soil quality, enhancing nutrient cycling, and promoting long-term soil health can effectively mitigate the adverse consequences of soil erosion and contribute to the attainment of food security.

4 Understanding Soil Regeneration Processes

The process of rehabilitating degraded soils is predominantly dependent on soil regeneration, which aims to reinstate the soil's vitality and productivity. The restoration of organic matter, the rebuilding of soil composition, and the reintroduction of essential nutrients are all integral components of this phenomenon. The comprehension of these processes holds significant importance in the development of efficacious strategies to address soil erosion and mineral depletion [25]. The process of soil renewal is predominantly dependent on the decomposition and accumulation of organic matter. The integration of organic matter, resulting from the decomposition of plant and animal materials, significantly enhances soil structure and water retention

[26]. Furthermore, it functions as a significant provider of vital nutrients necessary for the growth and development of plants. The augmentation of soil organic matter can be achieved through the implementation of various agricultural techniques, including cover cropping, composting, and crop rotation [27]. According to Schlaepfer et al. [28], the augmentation of soil organic matter content can be achieved through the implementation of cover crops, compost application, and crop rotation techniques, thereby serving as a viable approach to facilitate soil regeneration. In addition, soil microbes play a vital role in the process of soil regeneration. The facilitation of nutrient cycling, soil aggregation, and disease suppression is significantly enhanced by the presence of beneficial bacteria, fungi, and other microorganisms [26].

Microorganisms play a crucial role in the decomposition of organic matter, thereby enhancing the availability of nutrients for plants. Additionally, they contribute to the formation of durable soil aggregates, thereby enhancing soil structure. According to Soto et al. [29], the implementation of practises such as reduced tillage and the application of organic amendments plays a crucial role in promoting the establishment and preservation of a robust microbial community. These practises contribute to the regeneration of soil and provide support for the long-term viability of sustainable agricultural systems.

The comprehension of these processes pertaining to soil regeneration facilitates the adoption of efficacious strategies aimed at the restoration of soil health. Through the promotion of organic matter accumulation, enhancement of microbial activity, and improvement of soil structure, it is possible to revitalise degraded soils, mitigate soil erosion, and restore depleted essential nutrients. The implementation of these practises is crucial in the advancement of sustainable agriculture and the maintenance of long-term soil productivity and health [30].

5 Techniques for Soil Conservation and Soil Control

Numerous methodologies and managerial strategies have been devised to address the issue of soil erosion and facilitate the preservation of soil. The aforementioned strategies have the objective of mitigating soil disruption, improving the permeation of water, and mitigating the potential for erosion in both agricultural and non-agricultural environments [31]. Contour ploughing and terracing have been identified as highly effective methods for soil conservation. Contour ploughing is a farming technique that entails the deliberate alignment of ploughing activities with the existing topographical features of the land. The ridges and furrows created by this method are used to slow down the flow of water and reduce the likelihood of erosion. In contrast, the practise of terracing comprises the creation of horizontal platforms on inclined topography with the objective of preventing the quick flow of water and promoting the process of infiltration, hence mitigating the possibility for erosion [32]. Conservation tillage methods have been shown to be effective in reducing soil erosion. The discipline of leaving crop leftovers on the earth's surface or employing specialised machinery to reduce soil disturbance are examples of conservation tillage practises that can replace conventional intensive tillage methods. By keeping crop wastes, improving water retention, and easing organic matter accumulation, this method helps protect soil from erosion [33]. Moreover, the utilisation of cover crops plays a pivotal role in the preservation of soil. Cover crops are strategically sown during periods of crop dormancy, serving as a protective ground cover that mitigates soil erosion caused by external forces. According to Nahayo [34], these entities play a role in mitigating surface runoff, facilitating water infiltration, enhancing soil structure, and providing organic matter to the soil upon incorporation. Proper land management practises play a crucial role in soil conservation, when utilised in conjunction with these aforementioned techniques. The recommended strategies encompass the implementation of suitable crop rotation techniques, the adoption of effective grazing management practises to mitigate overgrazing, and the utilisation of responsible irrigation methods to mitigate soil erosion resulting from excessive water application [35]. Through the implementation of various soil conservation techniques and management practises, it is possible to effectively mitigate soil erosion, enhance water retention capabilities, optimise soil fertility, and facilitate the adoption of sustainable land utilisation strategies. The aforementioned measures play a significant role in maintaining the overall well-being of soil, safeguarding agricultural productivity, and ensuring the long-term sustainability of ecosystems [36].

6 Sustainable Agriculture Practices to Combat Soil Erosion

Sustainable agricultural practises provide a holistic strategy for addressing soil erosion and fostering the long-term well-being of soil. According to Tahat et al. [37], these practises place emphasis on the preservation of soil integrity, the optimisation of resource use efficiency, and the mitigation of negative environmental impacts. Agroforestry is an agricultural technique characterised by the deliberate integration of trees with crops or livestock, with the aim of promoting sustainability. Trees provide a multitude of advantages, encompassing erosion mitigation, nutrient recycling, and microclimate modulation. Erosion hazards are reduced thanks to the plants' vast root systems, which help to stabilise the soil [38]. Boardman and Vandaele [39] state that tree leaf litter has a major impact on soil fertility since it contributes to the buildup of organic materials. In the world of sustainable agriculture, crop rotation is a well-known and very effective method. Using a predetermined plan and schedule, crop rotation switches between growing different types of crops in the same area at regular intervals. Crop rotation is a farming activity that improves soil fertility, reduces erosion hazards, and disrupts the life cycles of pests and diseases. distinct plant species have distinct root systems and nutrient needs, therefore rotating crops can help the soil recover and reduce nutrient runoff [40].

In order to achieve sustainability in farming, it is crucial to adopt conservation tillage techniques. By leaving crop residues on the earth's surface or using sophisticated equipment that leaves the soil relatively undisturbed, these agricultural practises strive to minimise soil disturbance. According to Pretty [41], conservation tillage helps minimise erosion, increases water retention, and encourages organic matter accumulation by preserving agricultural residues.

In addition, cover cropping is an essential approach for preventing soil erosion, making its application crucial in the context of sustainable agriculture. Grown when other crops are resting, cover crops provide as a barrier between the soil and the elements, preventing erosion. The absorption of these components into the soil has several positive impacts, such as lowering surface runoff, increasing water infiltration, enhancing soil structure, and adding organic matter, as stated by [42]. Preservation of soil integrity, optimisation of resource use efficiency, and minimization of negative environmental impacts are crucial for ensuring agricultural productivity and safeguarding ecosystem health, and [42] argue that incorporating sustainable agricultural practises is an effective strategy for doing so.

7 The Role of Organic Framing in Soil Regeneration

Soil regeneration and the advancement of sustainable agriculture rely heavily on the methods employed in organic farming. Soil health, biodiversity, and ecological balance are prioritised through the use of organic inputs and management measures in agricultural practises [43].

The deliberate elimination of synthetic inputs like fertilisers and pesticides is central to organic farming practises. Organic farmers, on the other hand, use methods that don't need synthetic chemicals, such as compost, manure, and cover crops, to increase soil fertility and decrease pest populations. Organic inputs have been shown to improve soil structure, increase beneficial microbial activity, and lessen the likelihood of nutrient leaching and water contamination [44], as reported by Schreefel et al. [45]. Soil cover protection is a crucial part of organic farming. Mulching and cover cropping are two techniques used to preserve agricultural land. Soil cover acts as a barrier, protecting against the damaging impacts of rain and wind while also retaining moisture and creating a welcoming ecosystem for beneficial organisms. By maintaining soil cover, organic farmers can successfully reduce erosion and promote soil regeneration [46].

Crop rotations and diverse plantings are fundamental to organic farming practises because they increase soil biodiversity and improve nutrient cycling [47]. Diverse crops exhibit distinct root architectures and nutrient demands, thereby influencing the overall soil health and fertility. The aforementioned approach serves to mitigate nutrient depletion and facilitate the regeneration of soil resources [48]. The promotion of soil health, reduction of environmental impact, and improvement of long-term agricultural productivity are key objectives of sustainable agriculture, which are achieved through the prioritisation of organic farming and soil regeneration practises. Organic farming assumes a crucial role in upholding the sustainability of food production and safeguarding the well-being of ecosystems through its emphasis on soil conservation and regeneration [48].

8 Nutrient Management Strategies for Replenishing Minerals

The restoration of minerals in soils that have been depleted is a crucial component of the process of soil regeneration. The primary objective of nutrient management strategies is to rectify nutrient imbalances and guarantee the presence of crucial elements necessary for achieving optimal plant growth [49].

Organic amendments, such as compost and manure, are essential for the replenishment of minerals. The aforementioned amendments serve as a mechanism for gradually releasing nutrients, including vital minerals, into the soil. The integration of organic amendments by farmers leads to the enhancement of soil structure, stimulation of microbial activity, and facilitation of long-term soil health and fertility [50]. Crop rotation is an additional nutrient management strategy that holds significant value. Farmers have the ability to mitigate the excessive depletion of specific minerals in the soil by employing a crop rotation strategy that involves alternating different crops with varying nutrient requirements. Leguminous crops possess the capacity to perform atmospheric nitrogen fixation, thereby restoring the presence of this vital nutrient within the soil and diminishing the dependence on synthetic nitrogen fertilisers [51, 52].

Precision agriculture technologies provide accurate and targeted solutions for managing nutrients in agricultural practises. Soil testing and mapping techniques are valuable tools that yield precise data regarding soil nutrient levels, thereby facilitating farmers in the identification of regions exhibiting nutrient deficiencies [52]. According to Ahmad and Sharma [53], the utilisation of this information enables the application of fertilisers in a more precise manner, thereby reducing wastage and promoting efficient nutrient utilisation.

Green manures and cover crops contribute significantly to mineral resuscitation. When these plants are tilled into the ground, they begin to decompose, releasing nutrients that help boost soil fertility over time. The use of green manures and cover crops also protects the soil from erosion, which boosts the regenerative process [54, 55]. Restoring mineral levels and ensuring the soil's continued production and health requires the application of effective nutrient management measures [56]. Farmers can effectively regulate nutrient levels in the soil by utilising organic amendments, crop rotation strategies, precision agriculture technologies, and the incorporation of green manures and cover crops [57].

9 Harnessing Technology for Soil Health Restoration

The restoration of soil health has been revolutionised by technological developments, which have provided new approaches and tools to combat soil erosion and mineral depletion. Soil health can be restored through focused interventions thanks to improved monitoring and management made possible by modern technology [58].

For a thorough assessment of soil erosion and the location of vulnerable regions, remote sensing equipment is important. Soil erosion patterns and erosion-prone areas can be studied with the help of remote sensing techniques like satellite photography and aerial surveys. Policymakers and land managers benefit from this data because it helps them prioritise conservation efforts, develop effective erosion control techniques, and spend resources more wisely [59]. Optimising water use and reducing soil erosion rely heavily on sensor-based irrigation systems and soil moisture monitoring equipment. These devices provide real-time information on soil moisture levels, assisting farmers in making informed decisions about irrigation to avoid over- or under-watering. Effectively addressing erosion concerns, fostering favourable circumstances for plant growth, and contributing to water resource conservation by ensuring ideal soil moisture levels are all achieved through the use of these technologies, as stated by Mohammed et al. [60]. Soil health management is a promising area for the application of cutting-edge technology like machine learning and precision farming. Soil composition, weather patterns, and crop growth parameters are just few of the many variables taken into account by these technologies in order to provide tailored advice to farmers [61]. Through the analysis and interpretation of this data, precision agriculture technologies have the potential to optimise the application of fertilisers, reduce nutrient loss, and improve soil regeneration [62]. According to Chakrabortty et al. [63], machine learning algorithms have the capability to efficiently analyse large quantities of data and adjust recommendations in response to current circumstances. This enables farmers to make well-informed choices and implement accurate soil management strategies. The incorporation of technological advancements in the process of soil health restoration represents a notable advancement in the realm of sustainable agriculture. The utilisation of remote sensing, sensor-based irrigation systems, precision agriculture, and machine learning algorithms has facilitated the acquisition of significant knowledge regarding soil conditions. This has subsequently allowed for the implementation of focused interventions aimed at erosion control, nutrient management, and the enhancement of overall soil health [64]. According to Wu et al. [65], the utilisation of these technological advancements is of paramount importance in safeguarding the enduring productivity and sustainability of our agricultural systems, while simultaneously mitigating adverse environmental effects.

10 Conclusion

The issues of soil erosion and mineral depletion present substantial obstacles to the attainment of global food security and the maintenance of environmental sustainability. The interrelation among these matters underscores the pressing necessity for holistic approaches aimed at mitigating erosion, revitalising soil health, and replenishing crucial minerals. Implementing sustainable agricultural methods, such as agroforestry, organic farming, and precision nutrient management, it is possible to safeguard soil against erosion, improve its fertility, and foster sustained productivity over an extended period of time. The utilisation of technology and innovative methodologies enhances our ability to effectively monitor soil conditions, make well-informed decisions, and optimise the efficient utilisation of resources. As custodians of the planet, it is incumbent upon us to give precedence to the preservation and rejuvenation of soil. By implementing proactive strategies and allocating resources towards sustainable practises, it is possible to ensure a resilient and prosperous future for agriculture, ecosystems, and the entirety of humanity.

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Recycling Resources of Soil and Agroecosystem

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Abstract Realizing the reuse of agricultural organic waste (AOW) to ensure the sustainable development of agricultural production has been a key area of research over the past decade. As agriculture continues to progress, agricultural organic waste is emerging as the Earth's most abundant green energy source. The biggest obstacles in the restoration of agricultural utilization, however, are the accumulation of harmful fungi and insect eggs, the release of greenhouse gasses, and the inability of lignocellulose to break down agricultural organic waste. To address these problems, researchers have promoted the recycling of organic waste by pretreating agricultural organic waste (AOW), controlling the composting environment, and adding extra materials to create an environmentally friendly comeback of agricultural organic wastes towards the farm as well as encourage the expansion of the farming sector. The present study aims to provide recommendations regarding possible future associated research by providing a summary of current studies on composting problems, composting-influencing elements, and composting techniques.

Keywords Recycling · Agricultural organic waste · Resources · Composting · Environment · Agrosystem

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1 Introduction

As the global population grows and living standards rise, there is enormous pressure on agricultural output [1, 2]. The use of copious amounts of chemical pesticides and fertilizers, as well as the generation of agricultural waste, have a negative influence on food production and could potentially be hazardous to human health [3]. Globally, 1400 crores of organic matters are connected to lignocellulose annually, according to statistics [4]. A large portion of agricultural outputs are recyclable resources; therefore, inappropriate disposal exacerbates airborne pollutants by contaminating the surface and groundwater, wasting resources, and producing a large amount of greenhouse emissions [5]. Thus, the issue of how to safely and efficiently dump organic agricultural residue is one that concerns everyone on the planet [6]. The most prevalent organic material on Earth, lignocellulose, constitutes the majority of AOW [7]. If appropriately treated and returned to the field, it can achieve adequate processing of agricultural waste as well as lower the use of synthetic fertilizers and insecticides. Composting is one of the best strategies for promoting crop development, improving soil fertility, and increasing the reuse of organic matter [8, 9]. Composting farming lowers environmental pollution while reducing reliance on artificial fertilizers in agriculture [10]. Microorganisms, especially those that decompose lignocellulose, use complementary mechanisms to convert organic agricultural waste into a nutritional substrate that crops may absorb and use to compost once again on land [11]. Through aerobic composting, the complexities of organic matter are reduced to small soluble molecules in organic agricultural waste [12, 13]. Insect eggs, poisonous materials, and disease-causing microbes can be removed by maturation after composting [14]. Composting materials provide an abundance of nitrogen, phosphorus, potassium carbon, and additional vital elements suitable for crop nutrient requirements, serving as both a growing medium for the development of plants and a way to improve the soil [15] (Fig. 1). AOW recycling is a material cycle that moves through the atmosphere, soil, and ground [16]. Microorganisms are key players in this cycle and can reduce the composting cycle [17, 18], promote humification in the compost, help compost maturity, and accelerate the breakdown of organic waste (Fig. 1). However, this cycle has problems with lignocellulose degradation, the release of greenhouse gasses, and low-quality compost products [19]. In response to these issues, an abundance of research has recently been carried out to promote the recycling of organic farming matter, primarily through the addition of additives or the regulation of organic agricultural waste conditions prior to and during treatment (Fig. 2). Although several studies have addressed the conditions under which organic agricultural waste is treated, very few have explicitly examined the pretreatment of organic waste [20, 21]. Thus, to achieve ecological agricultural output, the concept of “taking from the land and using it for the land” is proposed in this chapter. The variables influencing composting, issues with composting, and consequences of composting materials on crop development are also covered in this chapter.

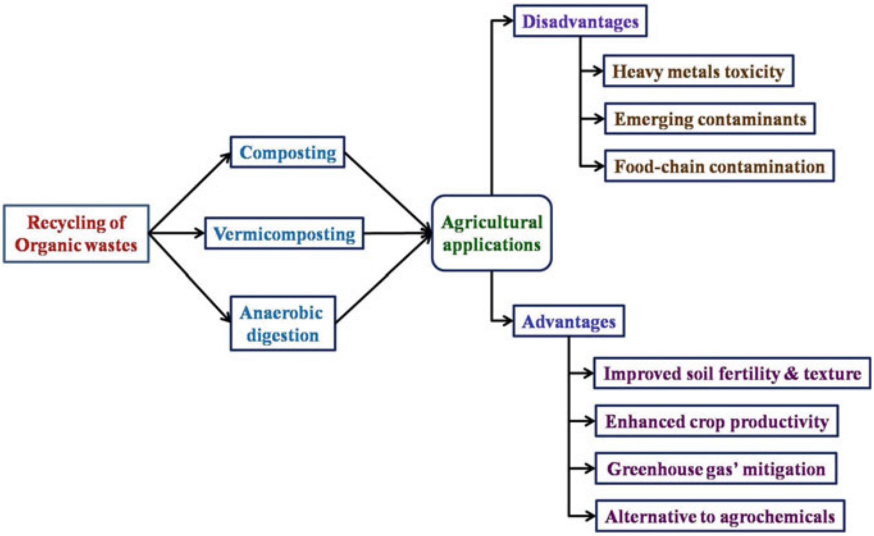

Fig. 1 Agriculture's use of organic waste recycling: A thorough analysis

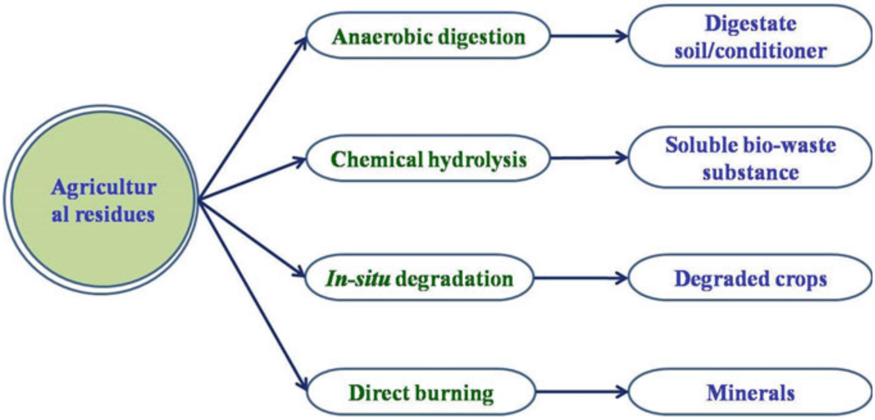

Fig. 2 Agricultural waste leftovers are converted to biomass for various uses

2 Lignocellulose

The bulk lignocellulose is often composed of hemicellulose from 15–25%), cellulose (38–50%), and lignin from 15–25%) [22, 23]. Cellulose is the main structural element of plant cellular walls and is densely packed and consistently structured. Lignin is an aromatic polymer composed of oxygenated phenylpropanoids and their derivatives, while hemicellulose is a polysaccharide composed of monosaccharides such as sugars. The interaction and covalent bonding of these components result in a rich and complex biological network arrangement [24].

2.1 Cellulose

Cellulose is a major component of lignocellulose and a complex carbohydrate [25]. The primary and minor aspects may differ between species; however, general directions are always present. A linear chain of β-1,4 glucose makes up the polysaccharide structure of cellulose, which is composed of an enormous quantity of backbone pieces joined by hydrogen bonds to create areas of crystallization [26]. Because of its thick networking and resistance to both biological and chemical breakdown, which greatly slows the pace of biodegradation, cellulose can only undergo physical and enzymatic processes from its surface [27]. The hydroxyl groups found in sugar molecules incorporate H^+ ions within as well as outside of the compound to strengthen the crystallized structure of the cell walls and make knowledge of hard-for water and appropriate digestive enzymes to penetrate it. The transparent region of cellulose is composed of regular arrangements of cell-wall molecules [28]. Research has shown that when the lignocellulose region approaches the nanoscale level, the accessibility of the degradation enzymes increases significantly [29], which facilitates the rapid breakdown of cellulose [30]. These associated hydraulic enzymes that break down cell walls into simple carbohydrates are derived from the glycosyl hydrolase family [31].

2.2 Hemicellulose and Lignin

The abundance of hemicellulose and lignin in organic matter effectively blocks cellulose from being accessible to hydrolytic enzymes, which is the single cause of lignocellulose's capacity to resist destruction [32]. The second most common polysaccharide after cellulose is hemicellulose, an elongated diverse polymer consisting of 1,4 xylopyranosyl groups joined by β-1,4-glycosidic linkages [33]. Pentose, hexose, and acetyl groups together with cellulose typically comprise the structural unit that comprises hemicellulose [34]. Hemicellulose undergoes hydrolysis simultaneously with cellulose. Hemicellulose, a non-crystalline material with shorter, more interconnected chains than cellulose cell walls, binds lignin and cellulose together [35]. The non-crystalline, heterogeneous, three-dimensional coagulated polyphenol polymer, known as lignin, is closely linked to hemicellulose [36]. It consists of basal cinnamyl ethanol, coniferyl ethanol, and mustard ethanol combined in an oxidative manner [37]. Utilizing lignocellulose becomes more difficult owing to the complexity and heterogeneity of the lignin structure caused by the variety of these monoalcohols and the unpredictability of the connections [38, 39]. Plant cellular walls contain cellulose, which is shielded by ligno-carbohydrates and prevents microorganisms from breaking down lignocellulose [40]. Eliminating hemicellulose and lignin increases the size of lignocellulosic pores, allowing hydrolytic biocatalysts to interface with lignocellulose pore materials and carry out hydrolysis [41]. Studies have shown that the first step in the breakdown of lignin is the hydrolysis of the aryl glycerol-β-aryl ether link along with the biphenyl linkage by microorganisms, which are important domains for microbiological hydrolase breakdown [42].

3 Lignocellulose Pretreatment

The covalent or non-covalent bonds that bind the constituents of lignocellulose together form a lignocellulosic matrix, which confers a robust natural defense against breakdown by hydrolytic biocatalyst [43]. To encourage the hydrolysis of lignocellulose, this disobedience must be overcome with pretreatment [44]. Pretreatment is mostly used to increase the cellulose surface area, alter the cellulose crystal structure, and facilitate lignin hydrolysis [45]. Physical, chemical, physicochemical, biological, and combination pretreatments are options for lignocellulose [43]. Increases in lignocellulosic porosity can be achieved using these pretreatments alone or in combination [26]. The substrate is hydrolyzed more quickly when it is changed by hydrolytic enzymes from its natural form to a more easily digested form [24]. Various pretreatment treatment approaches also provide varying results, and in practice, the best option is chosen based on particular circumstances and financial losses. The optimal lignocellulosic pretreatment should be effective in the following ways: (1) enhance sugar production or the ability to make sugars following digestion by enzymes [21]; (2) avoid carbohydrate decline; (3) halt the synthesis of compounds that obstruct afterward fermentation as well as hydrolysis methods; (4) be economical; (5) be environmentally sound; and (6) be simple to perform and involve less effort.

3.1 Getting Ready Physically

The act of preparation reduces cellulose crystal clarity to varying extents by disrupting the lignocellulose structure [46]. The key is to expand the substrate's specific area through physical means to broaden the region of contact between it and the hydrolytic enzymes and boost the effectiveness of degradation [41]. Various studies have indicated that the primary factors influencing the enzymatic breakdown of lignocelluloses are the surface region, particle size, and pores [26, 47]. Its advantages include a small amount of sugar, ease of use, and environmental friendliness [46]. However, the considerable power and intake associated with the treatment increases the cost of production (Fig. 2).

3.1.1 Smashing Mechanically

By mechanically pulverizing lignocellulose into particles 0.2–2 mm in size, the amount of polymerization and crystallinity decreased. Wang et al. increased the production rates of xylose and glucose from 25 g/L to 45 g/L and from 19 g/L to 40 g/L, respectively, after mechanically pulverizing the maize stover [48]. Furthermore, Ji et al. found that the amount of glucose produced increased from 35.29 to 81.71% when the biological matter was ground down to cellular size [46]. Therefore, it is incorrect to pursue a smaller size with increased energy consumption. It can be inferred that the quantity of lignocellulose particles affects the rate of transformation of biological matter, although the particle diameter also affects the amount of energy used. The primary barrier to the broad application of mechanical treatment in industries is that it consumes a lot of energy and does not produce any inhibitory chemicals; however, it is a prerequisite for treating AOW [49].

3.1.2 Processing with Microwaves

High-frequency vibrations of molecules with polarity with cellulose convert the electromagnetic field energy into thermal energy. A sequence of physical and chemical processes, such as expansion and thermos, modifies the internal structure of lignocellulose. In some studies [51], electromagnetic processing frequently works in tandem with additional pretreatment techniques to address the problems of minimal treatment performance and improper heating among various pretreatment techniques [50]. Chen et al. improved the digestion of cellulose by a factor of two to five by promoting the elimination of lignin and xylan using electromagnetic treatment [52]. The biggest drawback of microwave pretreatment is its high cost, despite its many benefits, including its environmental friendliness and energy-efficient use.

3.2 Pretreatment with Chemicals

Lignocellulose undergoes chemical processing with reagents such as hydrogen peroxide, acids, and alkalis. This encourages the breakdown of cellulose by mainly dissolving and destroying both hemicellulose and lignin during the course of treatment; however, because chemical reagents are utilized, it is easy to create contaminants in the environment along with various problems [53].

3.2.1 Preliminary Alkali Treatment

Alkali solutions such as calcium hydroxide, sodium hydroxide, and sodium carbonate produce structural changes in lignocellulose by esterifying the glycosidic connections in the material [54]. Alkali pretreatment can eliminate hemicellulose and lignin from cellulose, which promotes its hydrolysis and increases porosity [55]. Haque et al. showed that at 105 °C, a two% NaOH solution eliminated 84.8% and 79.5% of lignin and hemicellulose, respectively [56]. The interconnected hydrogen bonds of the cellulose molecules were broken by the alkaline prior to treatment, which significantly reduced the crystallinity of cellulose [57]. Furthermore, the amount of cellulose treated with the enzyme mixture increased with the removal of lignin and hemicellulose. Although alkali pretreatment can enhance the enzymatic efficiency of lignocellulose, there are significant obstacles in its practical application, such as the need to neutralize residual solutions, the creation of inhibitor compounds, and additional pollution.

3.2.2 Acid Pretreatment

Acid pretreatment is more effective than alkali pretreatment in removing “hemicellulose from lignocellulose,” breaking down the crystallized portion of “cellulose,” and increasing the availability of enzymes that hydrolyze “cellulose” [43]. For example, hemicellulose and lignin were eliminated in 59.5% and 13.3% of bagasse generated from sugar cane through the use of “diluted sulfuric acid” by Bukhari et al. [58]. In addition to decreasing the crystallinity of lignocellulose, the acid–base pretreatment technique significantly increases the sugar yield [45]. A study that treated “rye straw using diluted acids” at dosages ranging from 0.5% to 2.0% produced 69% cellulose saccharification [59]. The disadvantages include the fact that lignin is left behind, and the production of inhibitory substances such as acetic and formic acid [21]. Additionally, the acid mixture typically leads to oxidation in equipment and requires significant quantities of alkalinity to neutralize the substance that was treated [60], which can result in hazardous chemicals along with an increased cost of treatment [61].

3.2.3 Pretreatment with “Organic Solvent”

Propanol, ethanol, methanol, acetic acid, formic acid, and peracetic acid were the main chemical solvents used. Effective lignin removal and improved lignocellulose enzymatic accessibility are made possible using organic solvents. It is safe and environmentally friendly, and the solvent can be recycled [62]. This also improved the rate of cellulose hydrolysis. Choi et al. divided the two types of hemicellulose into hydrolyzed products, which they then treated for ten minutes at 160 °C with 50% alcohol along with “1% sulfuric acid” [63]. This procedure produced hydrolysates containing 80.2% glucose. Karnaouri et al. employed isobutanol as a natural solvent to effectively delignify and fractionate *fagus* wood. According to the findings, hemicellulose and lignin removal reached 43.3% and 97.6%, respectively [64]. In real-world applications, biological solvents possess the disadvantage of being costly and environmentally unfriendly despite having a high penetration efficiency that enables them to swell, decrease cellulose crystallinity, and boost lignocellulose conversion efficiency [65].

3.2.4 Pretreatment with Ionic Liquid

With the aid of ionized liquid treatment at room temperature, a molten salt mixture consisting of "anions and cations"—lignin can be removed, and "cellulose crystallinity" can be decreased [66]. Lietal et al. found that ionic liquid pretreatment of willow branches produced better results than the "diluted acid pretreatment" with regard to lignin content, specific surface area, and crystallinity [67]. "Hashmi et al. prepared bagasse at 110 °C for 30 min using ionic liquids. The processed bagasse showed considerably reduced "lignin concentration and cellulose crystallinity", with digestibility of "dextran and xylan of 97.4% and 98.6%", respectively. Its benefits as a green solvent include excellent thermal stability, chemical conditioning, non-flammability, and chemical stability [69].

3.2.5 Pretreatment with Oxidation

By treating "lignocellulose" using peroxyacetic acid or "hydrogen peroxide", the oxidative pretreatment approach can significantly reduce the lignin content. The influence on cellulose is minimal, while the impact on hemicellulose is minimal [70]. Since oxidative pretreatment has a high degree of delignification, it is frequently employed in conjunction with other pretreatments [71]. After oxidative pretreatment, "Sun & Cheng et al. achieved enzymatic digestion of wheat and rye straw" at 89% and 57%, respectively [72]. It is more common in practice to utilize oxidative pretreatment since it is a reasonably mild technique, and it is challenging to develop inhibitory chemicals. The benefits of moderate temperatures, minimal addition requirements, and low pollution have made "Fenton pretreatment"—a form of oxidative treatment that pretreats lignocellulose using ferrous ion and H_2O_2 as the medium—more and more popular.

3.3 Pretreatment with Biological Agents

Techniques for biological preparation date as far back as the 1890s [3]. Black gadflies, earthworms, and other scavenger insects are the major components of the biological pretreatment approach. In comparison to other pretreatment techniques, the biological method offers a relatively simple approach that is also quite environmentally friendly because it does not produce any inhibiting compounds throughout the treatment procedure.

3.3.1 Management with Microorganisms

Appropriate hydrolytic enzymes that are necessary for the breakdown of AOW are secreted by bacteria and fungi [73]. Additionally, extracellular hydrolytic enzymes, which are more suited to degrading lignin and other substances, make up the majority of the hydrolytic enzymes produced by microorganisms [74]. Some of the microbes found in AOW can also break down lignocellulose, but because they are scarce and have weak degrading abilities, these microorganisms contribute to issues like limited composting effectiveness and subpar compost products [75]. The breakdown of macromolecular substances in organic agricultural waste is typically accomplished during the decomposing process of organic agricultural waste by introducing an organic agricultural waste stack using essential metabolizing microbes since extracellular enzymes are secreted by "exotic single or complex colonies of bacteria" that are adept at releasing pertinent hydrolytic compounds [76]. Smaller fragments of biopolymers break down into the pile more quickly, changing its microbiological makeup and improving the quality of decomposition [18, 77]. When paddy straw was treated with fungi treatment with greater levels of lignocellulolytic enzymes, Sajid et al. observed a substantial effect in the cellulose breakdown of the hay as compared to chemical treatment (79%) or control (61%). A significantly higher compost temperature during the final thermostatic phase was also seen in rice straw compost after fungus treatment, which enhanced lignocellulose degradation. Suthar and "Kishore Singh et al." composted wasted cardboard by using a mixed culture of fungus as a pretreatment; in the process, they lost 38.8% of the dry matter and decreased the proportions of lignin, cellulose, and hemicellulose [79]. An increase in the variety of microbial population activities, resource complementarity between ecosystems, a prolongation of the thermostatic stage of decomposition, a boost in the quantity of relevant decomposing microbes, an encouragement to secrete relevant digestive enzymes, as well as an improvement in the rate of degradation of decomposing resources are all potential benefits of microbe inoculation [80, 81]. The mild nature of the microbial degradation process and the absence of hazardous byproducts make it one of the safest, greenest, and most efficient processes [82], offering an environmentally friendly approach to AOW degradation [83].

3.3.2 Treatment with Insect Compost

The efficiency of earthworms in composting applications has been extensively researched up to this point [84, 85]. The primary component of vermicomposting is the "hydrolytic enzymes" present inside the mucus of earthworms; additionally, because the mucus of earthworms contains some nitrogenous compounds, vermicomposting boosts the metabolic activity of bacteria as well as promotes the breakdown of organic matter [86]. Second, earthworm involvement with organic matter life causes the pile to become looser, hastening the composting process [87]. The process of composting increased the ion-exchange capability (139.8%), pH (6.9%), and NO_3^- while it also decreased total C (31.2%) along with C to N contents (32.1%), according to Yu et al., who emphasized worms on decaying mushroom-based composting. This suggests that earthworm introduction could enhance composting consistency as well as accelerate composting decomposition [88]. In their studies, "Gong et al." used vermicomposting for composting maize straw subsequently discovering it may reduce releases of greenhouse gasses between 66.23% as well as 55.12% [89]. For these reasons, earthworm composting is a more economical, safer, and cleaner method of therapy. Numerous studies have successfully composted food and kitchen trash, animal manure, and municipal garbage using black gadflies [90–92]. Bortolini et al. noted adding an amount of black gadfly to composted chicken manure resulted in a 75% reduction in the compost's dry substances and the creation of an excellent substrate suitable for agricultural production [93]. The larvae of black gadflies primarily feed on waste materials heavy in protein and fat, hence they were successful in degrading certain organic agricultural wastes, including plant straw, but less successful at degrading other wastes [94]. Black gadfly inoculation experiments in AOW composts have been started, and positive outcomes have been attained by taking specific steps for enhancement. "Menino et al." improved the efficiency with the significant breakdown of digestive enzymes as well as enhanced the organic material, nitrogen, phosphorus, and potassium levels into composted outputs by inoculating black gadflies into ryegrass composting [95]. In addition to encouraging the breakdown of organic waste, the black gadfly also helps to limit greenhouse gas emissions while composting. When pig manure compost is combined with black gadfly compost, for instance, greenhouse gas emissions can be cut by 90% [96]. The drawback of black gadfly composting is that the materials produced are less biochemically stable and easily allow fruit flies and mosquitoes to thrive and breed [97]. Additionally, black gadflies have certain environmental needs that must be met.

3.4 Integrated Pretreatment

Each pretreatment method for lignocellulose can only effectively affect a specific portion of the material's structure. However, if several pretreatments are combined so that their benefits and drawbacks balance one another, the rate at which lignocellulose degrades can be markedly accelerated. In addition to mitigating the shortcomings of individual preliminary treatments, combined preliminary treatments have the potential to boost sugar synthesis efficiency, reduce inhibitor development, and shorten processing durations by 50%. Combining preliminary treatments makes organic materials more efficiently converted, but they also add complexity and expense to the composting processes.

3.4.1 Combinational Physicochemical Pretreatment

Steam blast processing signifies the immediate removal of "pressure from lignocellulose" under conditions of extreme Thermus and pressure steam, which causes kinetic breakage along with morphological reorganization. During this process, the two substances “hemicellulose and lignin” are taken out and evacuated from it to varying degrees [98]. Sulzenbacher et al. found a much-increased sugar production and reduced development of inhibitory chemicals when steam blasting wheat straw at 200 °C [99]. “With the highest lignocellulose enzymatic rate”, blasting over 210 °C over 10 min was the ideal treatment scenario [26]. However, a longer treatment time may, in some cases, lead to both a greater enzymatic rate and the formation of specific inhibitors. Attention should also be given to various inhibitory chemicals created during high-temperature and pressure processing, including “aromatic compounds, furanic acids, and organic acids” [100]. Considering that water is employed as the medium for treatment, there are no chemical reagents needed, the procedure is environmentally safe [101], and it is popular due to its advantages over alternative treatments, including its quick turnaround time and effective energy use [43]. Using the liquid form of ammonia to treat the untreated substance at an extremely low temperature and pressure, Ammonia Fiber Expansion (AFEX) bursts the raw material under pressure. Most form of “lignin or hemicellulose” gets destroyed and the crystalline form of cellulose is disrupted within a “solid-to-solid process that” bypasses the need for water washing or detoxification [102]. The enzymatic rate significantly increases following ammonia fiber swelling therapy, according to numerous investigations [103, 104]. Chundawat et al. report that the amount of xylose and glucose released from ammonia-swollen prepared maize stover was about three times higher when hydrolysis with an enzyme was carried out during extremely solid circumstances. Additionally, compared to dilute acid pretreatment, ammonia pretreatment yields less inhibited degradation products [104]. Pretreatment with liquid ammonia fiber expansion increases the cellulose’s enzyme activity and nitrogen content, which is good for microbial fermentation. The ability to retrieve and reuse liquid ammonium makes this process more viable as a pretreatment technique and requires less energy overall. For ammonia blasting treatment, effective ammonia recovery is a problem that must be carefully handled. Cost and efficacy can be detrimental for certain timbers with high lignin concentration [105]. Wet oxidation is a technique for processing the material at a temperature higher than 120 °C with oxygen and water [21]. Two reactions make up the process: a high-temperature oxidation reaction and a low-temperature hydrolysis reaction [106]. The process of treatment involved immersing initial substances in hot water for a predetermined period of time without the use of a catalyst. The aim had been to improve the cellulose’s enzymatic reactivity by letting hemicellulose in the lignocellulose dissolve through self-hydrolysis. The pretreatment pH was maintained between 4 and 7 to further prevent inhibitor formation [107]. “Ji et al.” enhanced sugar restoration by about 5.12% into 42.9% [108] of processed wood pulp waste. Wet oxidation reaction’s main benefit, which is advantageous for future scale-up manufacturing, is the ability to perform numerous reactions in a single phase [109].

3.4.2 Integrated Processing of Several Pretreatments

Examples include steam explosion treatments in conjunction with an alkaline solution preprocessing [101], moderate physical as well as chemical preprocessing in addition to bio-treatments [110], and low-concentration acid preprocesses mixed with bio preprocesses [111]. The lignocellulose breaks down more quickly as a result of these combination pretreatments, which also reduce cellulose's crystalline structure and modify its chemical structure to various extents. Diluted alkaline preprocesses were shown to effectively lower the level of hemicellulose of cellulose [113], while diluted acid preprocesses were found to successfully lower the level of lignin of lignocellulose as well as raise its metabolic rate along with generated glucose [112]. Chen et al. hydrothermally processed rapeseed straw over 45 min at about 180 °C followed by two hours at 100 °C with 2% Sodium hydroxide. The saccharification efficiency improved 5.9 instances more quickly than that of the untreated feedstock [114]. When maize stover was treated by "Wang et al." using 2% sodium hydroxide that 80 °C for two hours, and then O_3 application for twenty-five minutes that a beginning pH of 9.0, the greatest efficacy of cellulase hydrolysis was 91.73%. Both types of preconditioning optimized enzyme "hydrolysis, composition, and structure", as well as the characteristics of maize stover [115]. "Binod et al." supplemented microwave processing alongside an acid and base process (1% H_2SO_4 and 1% NaOH) to enhance the production rate for lowering carbohydrates by about 830 mg per gram [116]. Rate of lignocellulose breakdown was significantly increased by combined pretreatment, although there are still drawbacks, such as inefficiency in terms of energy and the environment.

A common form of treatment is the fusion of biological and mechanical techniques. First, mechanical treatment disassembles the feedstock's physical structure to make it more accessible to hydrolyzing agents [117]. After treating "wheat hulls with white rot and yellow spore fungi" as well as ultrasonic pretreatment, "Oliver et al." showed higher catalytic yields of glucose [118]. More frequently than mechanical pretreatments, biological approaches in conjunction with chemicals are used as pretreatments. The combination pretreatment produced greater "saccharification effectiveness" with reduced sugar production when compared to the separate treatments [119]. Xie et al. combined the use of "white rot fungi with an alkali/oxidation (A/O) treatment" to increase "reducing sugar yields by 1.10–1.29 times" [120]. After pretreatment, "lignocelluloses" are primarily found as "glycans and oligosaccharides". The preprocesses products may be entirely transformed into xylose and glucose [100], monosaccharides required through microbes to break down AOW, following enzymatic hydrolysis.

4 Factors Affecting the Regulation of Decomposing the Organic Agricultural Waste

Since decomposition is a complicated and variable process [121], where changes in each parameter create various effects, it is primarily controlled by elements including pile aeration rate, particle size, temperature, water content, pH, EC, and C/N [122]. Inadequate handling of the previously listed elements may lead to losses of C and N, the release of “greenhouse gasses”, the presence of infectious bacteria, low-quality compost, and occasionally compost failure [123]. In order to increase composting efficiency, lessen nutrient dissipation, and improve compost product quality, researchers are changing composting characteristics, managing the composting process, applying additives, and using other treatment methods [124].

4.1 Rate of Aeration

The efficiency of composting is primarily impacted by the rate of aeration, which in turn impacts the respiration of aerobic bacteria [125]. An inadequate aeration rate will leave the pile depleted of oxygen, leading to the production of ammonia as well as additional gaseous compounds [126]. “Han et al.” discovered how the low oxygen level of the pile causes ammonia to be generated and that the emission of the aforementioned gasses can be somewhat reduced when the oxygen content is increased [127]. Although excessive aeration rates can deliver enough oxygen and speed up the decomposition of organic waste, they will also remove the pollutant gas created during composting and lower the pile’s capacity to fix carbon and nitrogen [128]. On the other hand, if the heap isn’t turned, it will warm up locally and undergo an anaerobic development, which promotes the production of CH_4. The composting process presents this conundrum [129]. Therefore, improving the quantity as well as the frequency of aeration throughout the method of composting can aid in maintaining the nutrients in the compost and lowering gas emissions [130]. According to Kamarehie et al. [131], boosting the alternating frequency between two times per week to once per week reduced methane and nitrogen oxide releases and raised ammonia decomposition. As a result, changing the reverse frequency or postponing the change for different lengths of time will aid in N conservation and GHG emission reduction.

4.2 Amount of Moisture and Temperature

The development velocities as well as efficiency of the microbes present in composting are mostly influenced by temperature, which is a critical element in defining the maturity of organic manure [132]. The age of compost and the rate of lignocellulose decomposition are thus impacted [8]. The variance in compost temperature may be a reflection of how microbes use organic materials during the warming, thermophilic, and decomposing periods [75]. Because of the microbes' life exertion, when organic waste is infected with a microbial agent, the relative temperature in its heap increases rapidly; additionally, the thermostatic time frame for the heap is slightly extended [133, 134]. At heap temperatures lower than 40 °C, nitrifications, as well as denitrifying microbes are the main producers of N_2O. At these temperatures, easily degradable chemicals are primarily broken down by thermophilic microbes. Thermophilic microorganisms, primarily CH_4-producing bacteria, become active at temperatures over 40 °C [135]. Temperatures above 65 °C inhibit the activity of most microorganisms, decreasing the effectiveness of the pile's composting process, even though harmful microorganisms as well as worm eggs of worms are almost eliminated at these levels [136]. The majority of harmful bacteria and their eggs can be killed during the composting process by the high temperature, although this will result in "the loss of C and N" through "volatilization within the pile" [115]. As a result, regulating the compost's temperature alone is not sufficient to address the issues with composting. The material pile's oxygen carrying capacity is determined by the moisture level of the compost, which also controls the temperature of fermentation, the porosity of the material, and microbial activity [137]. The starting moisture level in the heap ought to typically be between 55 and 70% [138], which is particularly advantageous for composting, even if the moisture content will typically be changeable as part of the recomposing operation. However, the level of water is usually unregulated during re-composting, so low water content affects microbial movement inside the pile, which lowers the activity of bacteria on the organic solid material as well as their biological degradation. When there is water content of 65% or above, denitrification and N leaching may be the cause [139]. Even after correcting for feedstock type, the results of Pardo et al. [140] are in line with a beneficial association across moist amounts and Methane releases. Tamura and Osada noticed larger the moisture content in the substance, the larger "the greenhouse gas emissions" through experimental studies of composting at different water concentrations [141]. This might be because of the high-water content, which makes the pile anaerobic and encourages the formation of "greenhouse gasses".

4.3 Electrical Conductivity and pH

Both the degradation of AOW and the release of greenhouse gasses can be impacted by the dynamic pH variations that occur during the composting of organic waste. "Ammonification is prevented when the pH is low" and it is first lowered by the synthesis of organic acids [142]. Ammonia is released during the mechanism of "ammonification and organic nitrogen mineralization" because the breakdown of organic acids raises the pH as the pile's temperature rises [143]. Thus, pH affects "the ratio of NH_4^+ to NH_3 in the pile". "Liang et al." studied "the mechanism of NH3 volatilization under composting conditions" in order to verify that substantial ammonia volatilization happened at high pH [144]. Contrarily, Zhao et al. discovered that reducing the compost's pH would lessen NH_3 emissions [145]. Gu et al. got outcomes that were comparable. The cumulative NH_3 emissions and TN losses were reduced by 47.80% and 44.23%, respectively, by lowering the pH of the compost [146]. It would take a lot of work to keep the pH variation within a range that is appropriate for composting organic waste, which is obviously incorrect. pH changes are challenging to manage while on the method of composting.

4.4 C/N

One of the most important elements impacting compost quality is C/N [147]. The pace of microbial growth and lignocellulosic breakdown is impacted by the energy needed for microbial development, which is provided by carbon, and the main supply of "microbial growth and protein synthesis", which is nitrogen [148]. When microbial agents are added, carbon breakdown, nitrogen loss, and compost substrate degradation can all be accelerated [149]. The pile's ideal "carbon-to-nitrogen ratio is between 20 and 30:1" [150], as well as a low carbon/nitrogen can cause the compost substrate to accumulate more ammoniacal nitrogen and volatile fatty acids, which will lower the amount of CH_4 produced [151]. A compost pile should have a carbon-to-nitrogen ratio of 20 to 30:1 [150]. An excessively low ratio of carbon to nitrogen can result in the compost's substrate accumulating more ammonia nitrogen as well as aromatic fats, with any excess nitrogen being discharged as NH_3 [151]. A high ratio of carbon-to-nitrogen proportion in a pile can slow the cycle of composting since it can restrict the production of the humus [153] and delay microbial biological degradation as well as the metabolism of biological material [152, 153]. The pile becomes mature as as is reasonably safe when the C/N concentration goes less than 20 to 25 [154]. Regulating carbon/nitrogen alone will not solve the problems with composting because composting is not aided by either elevated or decreased C/N levels.

4.5 Stacking Exogenous Ingredients

Aeration amount, the outside temperature, pH, moisture content, Electrical conductivity, and C/N ratios are only a few examples of the variables that are present in composting and often interact with one another when one is changed. Because of these factors, scientists have considered including various substances in the process of composting in order to reduce greenhouse gas emissions, accelerate composting maturing, and improve the final compost's quality. These additives consist of physical adsorbents, biological ones, and chemical ones [155, 156]. Externally generated additions, by varying degrees, can regulate its C/N ratio, moisture level, pH, as well as gas emissions, and improve the quality of the compost generated by the pile [157]. Biochar is characterized by a broad surface area, enormous adsorption ability, high ability to exchange cations, and extensive amounts of pores. Applying biochar to compost increases its efficacy significantly because it provides a suitable dwelling habitat for microbes and regulates the amount of water as well as the porous of the compost [158]. Strong adsorption capabilities of biochar allow it to drastically lower carbon dioxide, nitrous oxide, and ammonia emissions during the composting process [159]. Li et al. found that by adding 10% biochar into the composting pile, nitrogen losses were reduced by 53%, while ammonia as well as nitrous oxide emissions were decreased by 48% and 31%, significantly [160]. This resulted in a 21-day composting procedure. "Manu et al." reported that after adding 10% biochar to the composting, it developed in 15 days and, in comparison to the control group, showed a 50% decrease in loss of nitrogen and a 58% decrease in ammonia [161]. As a result, adding biochar to compost helps the material mature to some level in addition to reducing gas emissions. This could be due to the biocatalytic function of biochar in composting, which accelerates the decomposition of all biological material and produces compost that is excellent quickly [162]. Chemical additions such as "$Ca_3(PO_4)_2$", "$Al_2(SO_4)_3$", "$CaCl_2$", "$MgCl_2$", "HNO_3", and "$FeCl_3$" can significantly reduce greenhouse gas emissions through the method of composting [163]. Chemical ingredients have been included in the pile in order to provide immobilization, reduce fuel emissions, and regulate the pile's physicochemical properties [164]. When Xiong et al. combined mature compost with Sulphur powder, they reported a maximum reduction in NH_3 emissions of 56.3% and a reduction in N_2O emissions of 36.9% [165]. Liu et al. added charcoal, magnesium phosphorus-calcium, and mushroom materials to the composting. While the incorporation of magnesium phosphorus-calcium reduced the release of contaminants as well as increased the number of nutrients in the composting, the presence of charcoal expedited the compost's maturity and reduced the emission of pollutants from the pile containing sulfur [159]. Even though adding chemical components may lower the compost's greenhouse gasses, these additives can be expensive, as well as it's unclear whether adding chemicals also results in the presence of salt ions, which could pose unknown and possible risks concerning the compost [166]. AOW breakdown is accelerated by microbial inoculation, which also lowers the pile's emissions of greenhouse gasses. In order to compost organic waste, microbial additions are typically used in conjunction with creatures like earthworms and black gadflies. To be more precise, biological waste is pretreated by the microbes prior to being inoculated with the critters for composting. The heat generated by the microbial breakdown of organic waste kills most of the pathogens and weeds along with worm embryos in the compost pile, causing the temperature of the compost to drop quickly. Inoculate the pile with earthworms or black gadflies as the temperature of the pile begins to fall to promote secondary composting and fermentation. Vermicomposting was used in conjunction with pre-composting, and Zhang et al. demonstrated that this combination resulted in vermicomposting emitting more CO_2 and less CH_4 and N_2O than the control [124]. The difference lies in the fact that Lv et al. carried out the composting process at different ratios of carbon to nitrogen. Compared to the baseline group, vermicomposting accelerated the nitrogen formation of minerals, delayed the production of methane, and raised the output of N_2O while promoting the decomposition of biological material [167]. To counteract the increasing output of N_2O, sorptive compounds can be added to compost to reduce N_2O emissions.

5 Potential to Influence the Growth of Plants

Among the many advantages of using decomposed agricultural organic wastes in crop production are increased soil quality, enhanced plant development, and increased resistance to diseases spread by the soil [168, 169]. It can boost crop output and nitrogen intake as it is taken back to the farm using the proper plow procedures, and it may even improve plant development patterns [170]. Numerous studies have shown the advantages of restoring developed as well as decomposing agricultural organic wastes in the soil. (1) Enhancing the activity of soil enzymes that are intimately associated with soil fertility, such as convertase, urease, and phosphatase [171]. (2) Reducing the number of harmful soil bacteria while promoting the growth of beneficial soil bacteria [172]. (3) Boosting soil permeability, porosity, huge size of particle micro aggregates, along with water resistance [173, 174]. (4) Nutrients like C, N, P, and K are produced during plant growth [175].

5.1 Compost Microorganisms' Impact on Plant Growth

After introducing microbes into AOW piles, the proper decomposing microbes use an ecosystem sensing (QS) system to regulate the behaviors of the microbial population, hence promoting the breakdown and metabolism of biological waste [176]. Compost products are used in crop cultivation to reduce soil pathogen prevalence, promote plant development, and endure external environmental stresses in addition to increasing soil biodiversity [177, 178]. Compost goods contain microorganisms that in addition improve cultivation conditions for vegetation as well as stimulate plant growth [179]. Because microorganisms produce considerable amounts of heat during the breakdown of organic wastes, this heap warms up quickly, killing out hazardous germs and seeds for weeds. This has a positive effect on managing soil-living infections within farming areas. The compost materials that have been returned to the field may reduce some plant disease microorganisms, such as "*Pythium irregulare, Pythium ultimum, Phytophthora nicotianae, Fusarium oxysporum, Pythium* sp., *Verticillium dahliae, Rhizoctonia solani,* and *Pythium* sp"., among others [180, 181]. According to studies by "Paned et al." on "tomato straw" composting products, the presence of composting materials decreased the organic matter of fungus wilt in the environment, which subsequently, in turn, elevated the expression of related catalysts like "β-glucosidase, dehydrogenase, and alkaline phosphatase" [182]. When "Jiao et al." introduced maize biomass composting alongside aerobics complicated species, they found that this eliminated harmful effects with different plants as well as soil microbes and improved maize yield, the earth's microbial biodiversity, farm microbial variety, along with the production of enzymes [183]. Pei et al. examined the impact of microorganism metabolites on plant growth while studying the interaction between core bacteria and metabolites during aerobic composting [184]. They came to the conclusion that composting can remove hazardous materials from trash and encourage plant growth. Compost contains a variety of microbes that are specifically involved in promoting plant development [184]. Examples of "*Xylella*" species have excellent ecological tolerance, can suppress crop diseases as well as may stimulate crop development [185]. "*Azotobacter"* species are capable of biological fixation of nitrogen from the atmosphere, chelating iron, promoting plant development, and strengthening plant resistance to disease [186]. Crops can be encouraged to absorb soluble phosphorus by compost products containing Bacillus and Actinomycetes species [187], and "spore-producing" bacteria that are proficient in lignin degradation are essential for the phosphorus breakdown and fixation of nitrogen in the soil [188], both of which promote plant growth. "Antoniou et al." found the increased height of the plant, fresh dried weight, as well as overall surface area of leaves compared to plants cultivated in non-composted compost. This discovery highlights the role that microbes play in supporting crop development and suggests that the community of bacteria within composting improves the overall health of plants in addition to helping them resist specific disorders [189]. Plant growth is influenced by the microbes in compost, while microorganism activity is influenced by plants [190]. "De-la-Pena et al." found that the microbial population's composition was influenced by shifts in a crop's development stage. For instance, the plant's blossoming stage causes a rise in the secretion of defense proteins [191]. Several investigations suggest the way host genes impact the structure of the inter-root microbial community [192]. The interroot of plants can release a variety of proteins, organic acids, polysaccharides, and amino acids that microbes can utilize, and these chemicals constitute crucial catalysts for microbial activity [193].

5.2 Composting Enhances the Environment for Plant Growth

Due to intense farming as well as ecological deterioration, the growth environment for plants has been steadily declining, which has had a detrimental effect on plant development and productivity. While water transport indirectly influences nutrient availability, the physical properties of composting materials utilized in farming may significantly impact plant transport of water, gasses in the surroundings, as well as thermal transfer efficiency over the growth of seedlings [194]. Products made from compost are additionally helping to improve the conditions in which crops grow. In addition, composting increases the amount of nutrients in the soil, reduces the negative environmental consequences of synthetic fertilizer use [196], and lowers the negative effects of high amounts of inorganic nitrogen on "inter-rooted soil and plant growth" [195]. Qayyum et al.'s research indicates that crop yields in the soils treated with organic compost were higher than in the unamended control group [197]. Additionally, the soils in the amended group had higher total N, P, and K contents.

AOW composting also produces humin, fulvic acids, humic acids, and amino acids, all of which encourage plant development and the spread of disease [198–200]. This can also increase the nutritional value of the soil and decrease the detrimental effects of high inorganic N contents on both "inter-root soil and plant development" [195]. Toumpeli et al. found that composting agricultural organic waste materials improved the physical and chemical features of the soil more than other approaches. The biggest reduction in soil N, P, Ca, Mg, and clay dispersion occurred after compost was added [201]. Qayyum et al. found that crop yields and "total nutrients, phosphorous, and potassium" in soils containing natural compost had been higher than in the control group (unamended soils) [197]. "Pei et al." used composting materials in a potted chard experiment; the plants growing with the treatment group outgrew the control group in terms of fresh weight and plant height by a factor of 13.69% and 84.37%, respectively [202]. Therefore, composting materials have been utilized in farming as they enhance plant growth conditions, increase the nutritional value of the soil, and decrease the negative environmental impacts of applying chemical fertilizers. Even though compost is a rich source of nutrients, most composts fall short of what crops need in terms of nutrients. Composted organic waste typically has a neutral to alkaline pH, high salinity, and low nitrogen content. In order to produce good yields, several leafy crops must have their nitrogen needs satisfied because nitrogen is crucial for the manufacture of a number of secondary metabolites, including ascorbic acid, antioxidant enzymes, and polyphenols like glutathione [203]. "Machado et al." mixed mineral nitrogen into biological compost to compensate for the nitrogen deficiency in the compost and achieve superior crop yields [204]. In agriculture, compost is commonly applied in combination of different fertilizers. "Plant growth, photosynthesis, antioxidant systems, and secondary metabolism" were all examined in Zulfiqar et al.'s" study on the impacts of composting "biochar, compost, and biochar-compost mixes. They discovered that combining compost with biochar improved plant development and physiological biochemistry; they found that proline and GB buildup was greatly reduced while "plant growth, chlorophyll content, photosynthesis," as well as antioxidant defense system performance were all dramatically increased [205]. The application of compost enhances the activity of many soil enzymes that break down including phosphatase and catalase and facilitates the conversion of the soil's organic nitrogen elements into forms that are more easily absorbed by plants [206]. Numerous studies have also discovered a wide variety of bio-stimulants in compost's final byproducts, including "phenols, lipids, ferulic acid, fatty acids, and sterols" [207]. Agricultural organic waste is capable of being composted to create a more stable and safe organic fertilizer that may ultimately be utilized for farming and biological recycling of resources. Because distinct AOW breakdown products contain a variety of nutrients and physicochemical characteristics, for this purpose, "Zhao et al." proposed a novel concept called reliable compost approach [208]. Aimed at encouraging compost diversity to suit the various organic matter and nutrient requirements of cropping systems. To enhance crop yield, the decomposing products must correspond to the properties of the surrounding soil and the plants that are sown. To achieve a better outcome is accomplished by coordinating the properties of the farming system, the compost, as well as the implementation techniques.

6 Conclusion and Suggestions for Future Development

The secret to ensuring the viability of AOW agriculture is to give it economic value and make it profitable. The goals of composting AOW for field treatment are to improve compost product quality, promote compost maturation, and reduce greenhouse gas emissions from compost. In addition to aggravating pests and diseases, destroying the environment in which plants grow, and stunting the development of the next crop, inadequate or poor treatment will also inhibit the development of crops and lower crop yield. Therefore, the right kind of human connection is necessary for the AOW composting process. However, there isn't a clear protocol for returning agricultural waste to the farm after making compost, which may be applied in practice and has the effect of reducing crop growth slightly. For AOW composting, there are a number of pretreatment and treatment technologies available, each with their own benefits and drawbacks that should be carefully considered before being chosen and adapted to the scenario at hand. The pretreatment of AOW using chemical, physical, biological, and combination methods as well as the incorporation of additives throughout the composting process have all benefited from research. However, the majority of composting methods use more energy and can even have unfavorable outcomes. Since organic agricultural waste originates in nature, harnessing nature's power to compost it is the greatest option. The enzyme-based processing method is less expensive and more ecologically friendly than other treatment techniques. When it comes to current compost methods, the primary problems with composting include "greenhouse gas emissions" throughout the process, dangerous compounds in the composting, and poor-quality compost output. The best, most affordable, and environmentally friendly composting techniques, considering the aforementioned problems, include mechanically crushing the AOW before composting, bringing the pile's beginning water absorption amount and Carbon/Nitrogen within an adequate level, introducing composting using beneficial microbes the fact efficiently break down biological material, along with enhancing the compost's quality by adding dead animals like the "earthworms or black gadflies" throughout the compost's cooling processes phase. In the future, the agricultural straw that has grown and composted can be utilized to grow the crop again, a "take from the land and use it" method of composting organic agricultural waste. However, the decomposition of AOW and the resulting depletion of certain minerals during an earlier harvest can often result in a deficiency of at least one of the essential minerals needed for the development of crops. On the other hand, good crop yields can be achieved by returning agricultural waste to the field with minimal amounts of mineral fertilizer, therefore minimizing ecological damage as well as increasing economic advantages. AOW recycling is the only way to achieve the greener evolution of farming because basically strives for better food with less input and of higher quality. In addition to farm productivity, it may promote high-quality, environmentally friendly agricultural development, environmental safety, soil health, and other factors that are critical to the continued advancement of agriculture's green development.

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Natural Occurrences of Soil Dilapidation

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Abstract One of the most difficult problems facing many parts of the world, particularly developing countries, is soil dilapidation, which is still a major hazard that is garnering attention on a worldwide scale due to practical reasons that are directly driven by natural phenomena. Despite the value of soil, its repercussions for dilapidation—possibly brought on by various physical, biological, and chemical processes produced by certain processes (both naturally occurring and induced by humans) that reduce sustainable yield—lead to a long-lasting, persistent devaluation of soil. Therefore, the goal of this review is to provide a detailed historical background of soil dilapidation, its natural occurrences, variables that contribute to these occurrences, mitigation and management strategies, and policy and regulatory approaches to soil management based on previously published material. Furthermore, a discussion and presentation of various technological approaches are provided to mitigate and manage the process of soil dilapidation and nature protection, along with the opportunities and prospects.

Keywords Soil · Pollution · Natural · Dilapidation

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1 Introduction

Global biodiversity losses and soil dilapidation are a result of advances in agriculture, urbanization, and mining as well as a decline in rainfall events. The ecosystem has been irreversibly altered by human activity and natural processes. This affects the potential for future soil use, as well as the attractiveness of the Landscape [1]. Soil is one of the most valuable natural resources on earth. It is believed that 90% of the global population depends on soil, either directly or indirectly, to fulfil most of their fundamental needs, including food, fuel, housing, security, lumber, and fibre [1–3]. Although soil is a timeless resource for wealth creation, it is not without problems, particularly when it comes to environmental damage [4]. Theoretically, a key component of agricultural and environmental sustainability (AES) is effective soil management, prevention, restoration, and monitoring of soil safety and sustainability. The soil has been more worn down as a result of constant or endless use, exploration, and exploitation [4, 5].

One of the most difficult problems facing many parts of the world, particularly emerging countries, is soil dilapidation [5–8]. Due to damaged and overused soil, Europe is the least affected, with Asia having the largest hint and Africa following closely after [7]. The majority of soil dilapidation, which is reported to occur in other developed nations of the world as well, is a result of man's ongoing or unceasing exploration and exploitation of the soil [6, 7]. At the moment, human-caused soil dilapidation is costing more than 10% of the world's GDP, jeopardizing the welfare of more than three billion people, and driving the planet towards the sixth mass extinction [9].

In general, the environmental issues caused by dilapidating soil are a severe and pressing concern that affects many parts of the world, particularly those in Asia and Africa [6, 7]. According to Bhunia et al. [10], both natural and artificial processes and activities can cause soil dilapidation. The causes of distressed and exploited soil, in contrast, are dominated by, in addition to natural sources, elements of socioeconomic activities, with the outcome being a decline in the primary output and services of the entire environment [9, 11]. Similarly, aside from appropriate observation and appraisal, the list of the factors that contribute to as well as the methods of identifying the causes of burdened and exploited soil, are somewhat challenging and incomplete [8]. The deterioration of soil quality or the decline in soil potential productive features are all examples of soil dilapidation [12].

Various biological, physical, and chemical processes that reduce feasible yield may lead to soil dilapidation, which will produce a long-term, persistent depreciation of soil. Human and/or natural processes and behaviours have a direct or indirect impact on these processes [13–15]. Our review will concentrate on the natural occurrences of soil dilapidation, including erosion, weathering, geological changes, and biological processes. One of the main problems with all soil development and dilapidation processes is the way the soil is structured, which interferes with the ecosystem's ability to provide its functions [16].

Due to a decline in agricultural output, leads to several environmental, economic, and socioecological issues, including poverty, poor nutrition and health, changes in demographics, increased environmental dilapidation, and modifications to the climate system [17, 18]. Malhi et al. [19] state that the climate system's change may be caused by either external irregularities resulting from inconsistent natural or human-caused external effects, or internal irregularities resulting from the climate system's natural internal progressions. As a result, since the middle of the nineteenth century, there has been an unparalleled increase in temperature records worldwide [9, 20, 21]. These current climatic fluctuations are among the pressing problems worldwide that are also in charge of soil dilapidation and vice versa.

A deeper comprehension of the interplay between production techniques, soil resources, and environmental circumstances is necessary to achieve the goal of sustainable management practices that remediate or prevent soil dilapidation [11, 12, 22]. For more than 25 years, thorough reviews have examined soil dilapidation, and many of them have linked these interrelated causes. Although the management and dilapidation of soils are site-specific processes, we contend that almost universal soil dilapidation agents will result in a set of optimum management practices. To achieve a management perspective that satisfies shared soil stewardship aims, we therefore want to highlight the natural occurrences of soil dilapidation and effective integrated management methods for reducing and restoring soil resources.

2 Soil Dilapidation

Barbosa et al. [23] define soil dilapidation as a decline in the productive rate of soil due mostly to the over-exploitation of natural resources by humans. Natural vegetation is typically replaced by human-subjugated arrangements by humans. Agricultural and forestry practices, the blending of the natural world with man-made structures, and other such arrangements are examples of these human-subjugated systems [24, 25]. According to the Food and Agricultural Organization's (FAO) definition, soil dilapidation is a sustained period of decline in the environment's effectiveness. Soil disturbance has an impact on the environment due to both natural and human influences. About 20% of agricultural soil, 30% of forestry, and 10% of grassland are suffering from the harshness of soil dilapidation [26].

Soil ecologies are essential components that support human livelihoods, maintain the viability of societal growth, and maintain healthy environments [27]. However, the fundamental advantage of soil's limitless worth and its consistent value have been largely overlooked and underappreciated, which has led to serious soil dilapidation that ruins environmental infrastructure and impedes the sensible development of many areas [28].

One of the most important problems facing most areas of the world today is soil dilapidation, which has resulted in several recurring, divisive restorations every ten years since the Dust Bowl era in the mid-West US [29]. Hailey's 1938 African survey dubbed this the "African scourge" [29]. The soil is the essential resource that undergoes the greatest quality loss during all environmental change processes, and a malevolent sequence may be seen in many processes of dilapidation [30].

3 Historical Context of Soil Dilapidation

In the past, research on soil dilapidation brought on by agricultural intensification began in the 1940s [31–33]; nevertheless, it was not until the 1970s that it garnered significant international attention [34]. Therefore, soil dilapidation is not a recent issue; in fact, many ancient cultures collapsed and dissolved as a result of soil dilapidation issues such as erosion and salinization [35].

A variety of factors, including soil use, cropping system, agricultural practices, deforestation, policies, political instability, and conflicts, can be categorized as biophysical, socio-economic, or political and contribute to soil dilapidation [36–41]. Similarly, Roy et al. [42] asserted that the primary drivers of soil nutrient losses include human activity, soil erosion, crop destruction, leaching, and depletion in gaseous forms. Agricultural soil fertility reduction is mostly caused by crop absorption, erosion, leaching, volatilization, inadequate management, and harvests without appropriate replenishments. Through agricultural practices such as cultivation, tillage, weeding, terracing, subsoiling, deep ploughing, manure and fertilizer addition, liming, draining, and irrigation, many soils have had their chemical, physical, or biological qualities altered [43]. According to previous studies [44–46], agricultural soil has grown to be one of the planet's largest terrestrial biomes. Sadly, people have been wasting such great resources by developing and growing cities on the most productive soils [35, 47, 48]. Because of the fast urbanization of productive agricultural soil, soil dilapidation forced farmers to search for fresh soil. In a similar vein, soil and soil exhaustion and dilapidation have also resulted from agriculture's intensification [8]. The inherent qualities of the soil (physical, chemical), the climate (precipitation, temperature), the topography (slope, drainage), and the vegetation (biomass, biodiversity) are the elements that influence the type of dilapidation [5, 36].

4 Guidelines for Assessing Soil Dilapidation Process

According to Lal [36], soil dilapidation occurs when the soil is unable to carry out one or more of the following essential functions:

1. Preserve and improve the gene pool while maintaining biomass production and biodiversity.
2. Control the quality of the air and water by filtering, buffering, detoxifying, and controlling geochemical cycles.
3. Maintain records related to astronomy, geology, and archaeology.

4. Support the socioeconomic system, as well as the aesthetic and cultural values, and give the engineering foundation.

Likewise, Hartemink [34] goes on to clarify the two primary rules that might be useful when determining the degree of soil dilapidation:

1. Visible indications of soil dilapidation in the field. These can include soil surface sealing or slaking, salt buildup at the surface, or compacted and dense soil layers. Poor crop growth may be a result of these characteristics, but it may also be brought on by other, less obvious signs like drought or an increase in pests and illnesses.
2. Crop yield trends. Although there are several conflicting factors, such as a buildup of pests and illnesses over time, an increase in weed infestation, or weather variations, this is likely the strongest indicator of soil dilapidation.

Oldeman et al. [40] produced the first approximation to map and assess soil dilapidation globally. Five distinct human intervention types have been identified by the Global Assessment of Soil dilapidation (GLASOD) as having contributed to the current state of soil dilapidation: deforestation, excessive grazing, agricultural practices, the overexploitation of the cover of vegetation, and bio-industrial and industrial activities [34]. According to GLASOD, soil dilapidation caused by human activity affects about 40% of the world's agricultural soil, and over 6% of it is so severely deteriorated that regeneration requires significant financial outlays. In Africa and South America, there was a significant reduction in soil fertility due to nitrogen loss, whereas in Asia's soils, the issue was less severe [40].

5 Factors Contributing to Soil Dilapidation

The biophysical process of soil dilapidation is made worse by political and socioeconomic variables. Numerous natural processes, such as weathering, erosion, geological processes, and biological factors, control the rate at which soil degradative processes occur (Fig. 1). According to research [49], poverty exacerbates soil dilapidation and can cause more serious problems on soils utilized in subsistence farming without outside assistance than on soils utilized for commercial farming with input.

5.1 Erosion

Soil erosion intensifies the dilapidation of the soil and vice versa. Erosion can occasionally occur before a reduction in soil quality, particularly when structural units are failing. In some cases, erosion can result in a drop in soil quality and start a degradative trend. Because soil erosion physically removes dirt in a vertical or horizontal direction and lowers soil quality, it might be a sign of soil dilapidation. Alluvial and

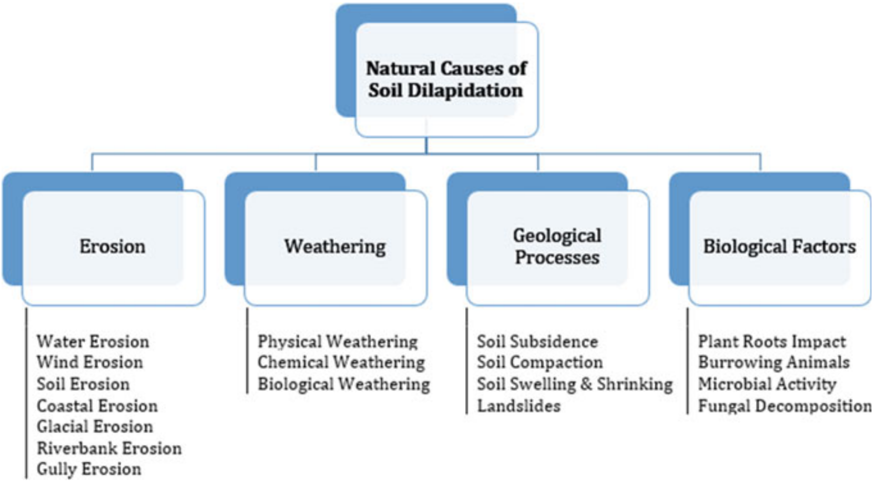

Fig. 1 Depiction of the natural causes of soil dilapidation

loess soils, which are rich in nutrients, were formed by a natural process that also changed the landscape. However, the quality of the soil and surrounding environment may suffer greatly if anthropogenic disturbances speed up the process.

Particles of soil are separated, moved, and deposited as a result of soil erosion. Erosion agents provide the energy needed for the task, and the energy source defines the kind of erosion that occurs (Fig. 2). The wind, water, gravity, and chemical processes in the soil are examples of natural energy sources or agents of soil erosion. The intensity of erosional processes is determined by the amount and rate of energy dissipation from various sources [50–52].

Fig. 2 An active erosion in northern, Nigeria

Detachment, the first stage of soil erosion, is brought on by the breakdown of organo-mineral complexes, which results in the creation of domains, macro-aggregates, and aggregates by the impact of raindrops, the shearing or drag force of water and wind, or the chemistry-induced dissolution of cementing agents [52]. Detached particles and micro-aggregates are moved by wind and flowing water (over-soil flow and interflow), and they are then dumped when the speed of the water or wind is reduced due to slope or ground cover [53]. Sediments must be separated from the soil mass or be in a state of separation before being transported downslope (or downwind). The time interval between detachment and ultimate deposition can vary from a few seconds to thousands of years, as can the physical displacement range from a few millimetres to thousands of kilometres [53, 54].

5.2 Weathering

Weathering is the process by which ground materials change as a result of nuclear radiation, the Earth's atmosphere, cryosphere, biosphere and hydrosphere. Hard ground mostly becomes soft ground as a result of weathering [55]. The most evident effects of weathering are landslides and unstable cut slopes, but soil and rock within tunnels can weather and endanger the stability of the tunnel. The geotechnical quality of completely buried ground beneath the foundations of surface structures may deteriorate over time as a result of groundwater and air seeping through it [56]. As we covered in our examination, there are three main reasons why materials weather: physical, chemical, and biological factors. A rock physically breaking down into smaller pieces that yet have the same characteristics as the original is referred to as mechanical weathering or physical weathering. mostly results from variations in pressure and temperature [55]. On the other hand, chemical weathering refers to the process via which components are added or removed from a mineral, changing its internal structure. Chemical agents operate to change the phase (mineral type) and chemical makeup of materials [57–59]. The availability of a surface for the temperature of the reaction and the existence of chemically active fluids are two factors that affect chemical weathering. Because of their increased surface area, smaller particles weather chemically more quickly than larger ones, causing breakdown, new mineral formation, and mineral solution. Since these react with the ground and groundmass material, the existence of water, groundwater, or air containing dissolved or vapour chemical agents is crucial [56].

Biological weathering happens as a result of an organism's daily activity. The biological breakdown of rocks caused by humic acids, microorganisms, and bio-erosion or destruction is one of the organic processes [60, 61]. The roots that sprout and the organisms of shells, lichens, cyanobacteria, algae, and fungi that penetrate the rocks on which they grow cause the modifications. Lichens, cyanobacteria, and fungi are responsible for the bioerosion of carbonate rocks, including limestone and dolomite, which makes a significant contribution [61]. These organisms inhabit vast areas and produce a great deal of fine-grained carbonate detritus of limestone sludge due to their continuous activities that have destroyed a great deal of rock throughout the geological era [58–60].

5.3 Geological Processes

Geological processes include soil subsidence, compaction, swelling and shrinking, and landslides have been cited in studies as causes of soil degradation [61–65]. These may come from long-term surface pressure brought on by urbanization, heavy mechanization in the processing of agricultural land, or high livestock grazing pressure brought on by intense grazing [62, 63]. This may also be the result of population migration and an expansion of the transport infrastructure [66].

5.4 Biological Factors

The term "biological factors" refers to the natural processes that tend to dilapidate the fertility and quality of the soil, including those carried out by humans, animals (burrowing), plants (roots), and microorganisms (fungal decomposition) [67–69]. Biological factors do have an impact, but it is not as evident as other factors. A region's microbial activity can be greatly impacted by an overabundance of certain bacteria and fungi through biochemical processes, which lowers agricultural output and the appropriateness of the soil's productivity potential [68].

6 Impacts of Soil Dilapidation

The environment, agriculture, and society are all significantly impacted by the multifaceted process of soil dilapidation. Soil dilapidation poses a severe hazard to people, particularly in developing nations like West Africa, where nearly 65% of the continent's soil is deemed to be dilapidated [23]. We identified and discussed the major impacts of soil dilapidation below.

6.1 Environmental Consequences

Soil dilapidation, often a result of erosion and improper soil management, has severe environmental consequences. It results in the loss of topsoil that has a detrimental effect on soil productivity because it is rich in minerals and organic matter [70]. Biodiversity is also affected, as soil organisms and microorganisms suffer, disrupting the soil ecosystem and diminishing overall biodiversity [70, 71]. Communities have been split apart, individuals evicted from their houses, construction projects have been wrecked, and agricultural soil has been abandoned due to widespread gullies like those in Fig. 2. Tree lodging and wind-blown dust have increased, posing health risks due to wind erosion. Moreover, pollutants such as pesticides and fertilizers, along with eroded soil particles, find their way into water bodies, causing pollution and devastation to aquatic ecosystems [72, 73]. Beyond the gradual loss of agricultural soil, soil erosion has other negative repercussions. Fish and other species have declined as a result of the increased pollution and sedimentation that have clogged rivers and streams. Flooding can get worse because dilapidated areas are frequently less able to hold onto water [72]. Sustainable soil use can lessen the negative effects on livestock and agriculture by reducing soil erosion and dilapidation as well as the loss of valuable soil due to desertification [5, 74].

6.2 Agricultural and Economic Impacts

The agriculture sector is primarily responsible for soil dilapidation. Lower crop yields as a result of topsoil erosion lead to lower agricultural production [73]. The requirement for extra inputs, including irrigation and fertilizers, which raises the cost of output, affects farming's viability economically. The loss of nutrient-rich topsoil in sub-Saharan Africa has been blamed for less than 1.5 t ha^{-1} of the 5 t ha^{-1} output potential of cereal crops over the previous 50 years [75]. In severe circumstances, it may become necessary to abandon soil, which would result in large financial losses for farmers and force them out of business. Due to these problems, there may be an increase in food costs and food insecurity throughout the world's food supply chain [74].

6.3 Societal Effects

Soil dilapidation has a significant impact on society in addition to the environment and agriculture. In the worst situations, people would have to relocate or migrate in quest of better living circumstances. Conflicts and societal unrest may result from this. Furthermore, because it makes nutrient-dense plants less accessible and affordable, soil dilapidation has an impact on nutrition and health [76]. Competition for limited resources, such as arable soil and water, can lead to social conflicts that affect relationships within the community. Additionally, cultural practices and traditions related to agriculture and soil use are eroded by soil dilapidation, which has an impact on the identity and legacy of communities in impacted areas. Holistic approaches that integrate economic, environmental, and cultural preservation with community involvement are required to address these societal effects [77, 78].

7 Mitigation, Management and Remediation Strategies

Potentially, a range of natural events and human activities, such as soil monitoring, management, adaptation, remediation and rehabilitation efforts, are necessary for the betterment and enhancement of explored, distressed and exploited soil [79–81]. In terms of soil remediation, each of these is personified. However, it may be necessary to determine the types, probable causes, and full degree of the dilapidation for appropriate soil remediation techniques to be efficient and successful [82, 83].

The kind of process causing the dilapidation determines how quickly it happens and whether it can be controlled [6]. The main natural processes that cause soil dilapidation are weathering, erosion, geology, and biological processes. Therefore, efforts to control dilapidation should focus on measures that will stop or lessen the direct effects of these drivers, increase infiltration rate, decrease runoff, and increase organic matter, all of which will restore soil fertility. These elements are divided into three categories: technological, agronomic, and both [84]. Agronomic technologies have been identified as a critical adaptation method for poor nations worldwide, particularly in sub-Saharan Africa, and they aid in water conservation [4–6].

7.1 Agronomic and Biological Measures

To protect soil surfaces from direct raindrop impact and to create rough surfaces that will obstruct lower drainage, agronomic and biological measures are focused on the utilization of fresh or dead vegetation. This is accomplished by using cover crops, which are cultivated to restrict nutrient loss through leaching or runoff, prevent soil erosion, and provide a protective cover [85]. The crops contribute to boosting nutrient management by either acting as a source of nutrients or by recycling nutrients to successive crops from decomposing plant leftovers. Thus, soil dilapidation is decreased. By providing N through fixation, the use of legume cover crops can increase crop yields when compared to non-cover crops [86].

In addition to preventing soil erosion and maximizing nutrient cycling, some measures to increase carbon sequestration include the use of cover crops and better handling of crop remains. The present goals of soil carbon sequestration are to raise soil quality and lower atmospheric CO_2 concentrations. According to Lal et al. [36], residue management and conservation tillage in agriculture in the United States have the potential to sequester anywhere between 35 and 107 million mg C yearly. While efforts to sequester carbon in soils should be made, the primary goal should be to halt the increasing loss of soil organic carbon (SOC). This is because it is clear that putting in place the practices, policies, and technologies needed to realize the potential that has been projected would be difficult.

Moreover, farm productivity can be increased by the utilization of animal grazing. Without affecting crop production, doing so can control weeds, lower feed costs, improve soil organic matter, and disperse nutrients. In the Southeast United States, moderate animal grazing can improve soil quality and productivity by enhancing soil organic matter and nutrient cycling; however, excessive grazing can degrade soil properties by reducing soil organic matter (SOM) [87]. In the southern Great Plains, surface compaction from cattle grazing on green dual-purpose wheat without corrective tillage enhanced the soil profile's resistance to penetration [88]. They also observed less water saving, which resulted in lower crop yields after three years, when compared to ungrazed no-tillage cropping systems.

To increase agricultural productivity, excessive tillage and grazing can deteriorate soil by damaging or distorting the soil's structure [89]. The final results include compaction and a reduction in space, which by definition raises bulk density [91. For instance, it has been demonstrated that soil compaction in northwest Ohio limits root growth, water flow, and infiltration capability, all of which in turn affect crop productivity [90].

7.2 Technological Strategies

Numerous methodologies can be employed to investigate soil dilapidation and the repair procedures of the soil.

7.2.1 Geographic Information Systems (GIS) and Remote Sensing (RS) Procedures

Geospatial technology is one of these technological approaches; examples include field or ground measurements utilizing geographic information systems (GIS) and remote sensing (RS) procedures [91]. Large soil areas may be easily measured with RS, which is also considerably more affordable than field or ground measurements. Therefore, one of the best tools for determining the bulk of soil dilapidation's effects over an extended period is satellite data [91, 92].

Achieving sustainable advancements in cities requires extracting variations in soil utilization and soil protection, as well as their environmental consequences. According to certain reports, degraded soils may be identified by combining GIS and satellite data [93]. Furthermore, as mentioned by Shareef et al. [94], studies are being conducted on the use of geospatial technology to fuzzy analytical hierarchy process (FAHP) methodologies for soil dilapidation and reclamation.

Long-term changes in soil cover and biomass activity can be consistently observed using satellite-derived remotely sensed Earth Observations (EO) [75, 95]. This has reportedly been widely used to track the dynamics of desertification, forest dilapidation, or changes in soil cover [96, 97].

However, some regions—particularly developing regions—have difficulty obtaining and/or producing the necessary data for tracking soil dilapidation using EO data [75]. To assess the impact of the global datasets (GDS) on soil cover and the dynamics of soil productivity derived from remotely sensed EO data, the UNCCD initiated an “LDN target-setting pilot project” including fourteen countries in 2015. According to reports, several countries were able to use both their national statistics and global databases to determine their goals [98]. Even though the chosen GDS has helped to moderate coarse spatial resolution (250 m to 1 km), it presents difficulties for the accurate analysis of soil dilapidation, particularly in areas with mountains, small soils, and extremely uneven surfaces [75]. Thus, techniques for creating improved spatial resolution indicators—such as those measuring 10 to 30 m—must be created to assess soil deterioration.

7.2.2 Nanotechnology in Soil Remediation Processes

Innovative methods, like using nanotechnological machinery to monitor and manage the emergence and challenges of soil remediation, like nano-biosensor mechanisms, are crucial and must be investigated, developed, and advanced, as was previously mentioned in the introduction section. Nanotechnology (NTech) is a developing field within science that studies nanomaterials (NMs) [97, 99, 100].

According to the US Environmental Protection Agency, nanotechnology (NTech) is a cutting-edge field of study that focuses on understanding, managing, controlling, and observing materials with sizes (dimensions) ranging from 1 to 100 nm and unique physical characteristics that allow for innovative applications [101, 102]. According to Mukhopadhyay [103], this description of NTech is somewhat rigid in terms of size (magnitude) dimensions. Nonetheless, the proficiency and aptitude of these NMs in solving problems have gained increased attention. Other attempts to define New Mexico from the perspectives of the agricultural and environmental sectors include particulates that are simultaneously colloidal and have sizes ranging from 10 to 1,000 nm.

Particulates that are colloidal and range in size (magnitude) from 10 to 1,000 nm are included in additional attempts to characterize NM from the agricultural and environmental sectors [104]. NTech is currently the branch of science that designs and manufactures machinery in which all particles and chemical/organic linkages are exactly quantified [102]. It is a set of competencies that are implemented when our technology originates close to the limits established by modern physics, rather than a collection of particular processes or tools [103].

The large-scale intrinsic constraints and challenges in ecological and agricultural processes will surely be addressed by NTech for AES. This may incorporate NM with variable dimensions that complete tasks in environmental and agricultural settings. The expanding and changing uses of NTech in the fields of agriculture and the environment necessitate a constant implementation to completely rely on this NM’s capacity for problem-solving, which is unlikely to be strictly observed to a greater extent than 100 nm.

The application of these nanotechnological procedures using nano-biosensors has been considered by some scientists/researchers as one of the dynamic aspects in the elimination, monitoring, and management of soil because it offers solutions to the ecological issues that lead to adverse effects confronting the entire ecosystem.

This has shown promise in addressing some of the complex and emerging problems associated with soil restoration, particularly those about ecological sustainability and public safety [102–104].

7.2.3 Engineering Approach

Early efforts largely centred on the use of contour terraces to reduce and regulate soil dilapidation. Although it generally functioned effectively, there were significant drawbacks because the terraces regularly collapsed following intense precipitation events [12]. Furthermore, because the spacing between terraces varied greatly, contour terraces performed poorly as machines got bigger. In an attempt to solve this issue, parallel terraces were occasionally employed; however, this required additional soil movement, increased construction costs, and frequently resulted in issues with soil fertility [105]. We believe that the most effective strategy for repairing damaged soils in North America will involve sustained efforts to replenish soil carbon through lowering tillage intensities and keeping a suitable quantity of crop residue.

7.3 Policy and Regulatory Approaches

There is a need for the complete provision of efficient rules and regulations in light of the thorough assessment of the numerous causes of soil dilapidation and the major impact these processes have on the environment, agriculture, and society. To prevent the eviction of residents from their historic habitat, public policies that promote the development of social capital among all stakeholders—especially the original residents and property owners—must be suggested and evaluated by qualified experts [106]. Governmental organizations have to make sure that both the local proprietors and potential outside investors get a fair deal. This plan is in line with suggestions for revitalizing deteriorated soil in different regions of the world [107].

8 Future Prospect

Sustainable government policies can assist in reducing the threat of soil dilapidation, with an eye towards a brighter future, a cleaner and bluer environment, awareness raising in schools, an increase in soil literacy, and soil health training, particularly in Asia and sub-Saharan Africa [108]. The potential for using nanotechnology (NTech) for AES in the environmental and agricultural domains is remarkable. It is a relatively recent field of study, having been around for just over 20 years. However, we have very little opportunity to investigate NTech in all agricultural sectors as conventional agricultural processes become more and more inadequate, especially given the advent and difficulties of soil remediation, and as demands exceed the carrying limits of the global environment. It is often recognized that the accumulation of national wealth depends on the application of cutting-edge technology [100, 109]. The aforementioned opportunity could support significant programmes aimed at lowering soil dilapidation processes.

9 Conclusion

The mitigation of climate change, AES and other important ecological advancements are fundamentally dependent on the proper use and exploitation of soil concerning soil safety and sustainability. The soil has been continuously and endlessly used, explored, and exploited, which has resulted in its dilapidation. Beyond the worldwide pandemic, soil dilapidation is a global problem that endangers human development everywhere. With an emphasis on causes, effects, and future possibilities, this study offers some solutions for addressing the natural occurrence of soil dilapidation. We determined that some of the main causes of soil dilapidation include weathering, erosion, and biological and geological processes. Measures to regulate these drivers should be taken to protect the soil from their direct influence, create soil organic matter, and improve the soil's ability to withstand water penetration as part of mitigating, managing, and remediating the effects of soil dilapidation. Prominent approaches in agronomy, technology, and policy were suggested. The UN sustainable target number 15, "Protection of life," will be much closer to being achieved if remedies to soil dilapidation are offered.

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Soil Regeneration and Influencing Factors

Regenerative Agriculture for Food Security

Gabriel Gbenga Babaniyi, Femi Ibrahim, Ulelu Jessica Akor, and Oluwatosin Emmanuel Daramola

Abstract Various stakeholders in the government, corporate, and nonprofit sectors exhibit a growing interest in regenerative agriculture. This includes practitioner organizations in the field of regenerative agriculture and the expanding academic discourse around it. However, this article aims to provide a research-driven clarification of how specific individuals and organizations have interpreted or applied the term "regenerative agriculture.“ The efficacy of conservation agriculture in preventing, arresting, and even reversing soil degradation while enhancing soil quality has been repeatedly demonstrated. Agriculture is poised to play a pivotal role in addressing the global food challenge, as it contributes both to the predicament and offers a potential solution. Across a broad range of agricultural settings, there are a number of transformative agricultural techniques that are quickly evolving, vibrant, and diversified. In truth, environmental components like economic, institutional, and political restraints, as well as visibly skewed power systems, can operate as barriers to such transitions. Thus, the institutional, political, and economic environment in which social diffusion processes take place determines their potential. Because of this, it is obvious that the forces causing change are not just present in farmers and their individual learning processes, but also spread out among smaller and larger structures, which consequently also hold a large share of the responsibility for fostering such transitional processes. The soil is fundamentally connected to food security. Land usage must be based on what it is capable of in order to prevent future degradation. By taking care of the soil, we can either seek to use regenerative agriculture to try to make up for what has been lost, or we can preserve the soil's capacity and condition. This inquiry has illuminated ways to enhance and ensure the well-being of current and upcoming generations by considering food security and soil security as intertwined

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concepts. To safeguard food and nutrition security, it is imperative to cultivate novel perspectives.

Keywords Regenerative agriculture · Soil security · Food security

1 Introduction

Amid interconnected socio-ecological crises posing threats to ecosystem services and food security, agriculture plays a pivotal role in addressing sustainability challenges [41]. The expansion of urban, suburban, and exurban development into rural and agricultural areas has raised public concerns about land usage, predicting extensive farmland loss [57]. Population increases are linked to farmland losses, intensifying worries about declining agriculture in urban areas [6]. Continued global population growth negatively impacts environmental systems, necessitating a better understanding of Earth processes and a reduction in our environmental footprint. The rising demand for food and agricultural goods due to population growth underscores the importance of ensuring constant access to sustainable and sufficient food for all individuals, safeguarding the right to food [15]. The use of nitrogen fertilizers and pesticides has significantly boosted agricultural land productivity, contributing to the population explosion. Synthetic nitrogen fertilizers, particularly the Haber–Bosch process, played a crucial role in population growth from 1.6 billion in 1900 to 7.4 billion in 2016 [72]. Estimates suggest that without synthetic nitrogen fertilizers, only 3.5 billion people, half the current global population, could be fed [16]. However, large-scale monoculture farming, synonymous with industrial agriculture, has raised sustainability concerns, emphasizing the need for alternative, low-input practices [59].

Land, beyond its utilitarian roles, holds economic, social, and environmental value, and its degradation poses challenges to human well-being. Soil deterioration, chemical imbalances, and nutrient loss contribute to soil degradation, diminishing the quality and quantity of available food, leading to crop failure and starvation [37, 55]. Conventional agriculture, relying on synthetic fertilizers and pesticides, has brought about environmental and health issues, necessitating a shift toward sustainable practices [60]. The expansion of modern agriculture since 1950 has contributed to global challenges, including disruptions to the nitrogen cycle, loss of biodiversity, climate change, freshwater consumption, and changes to the land system. These challenges underscore the need for a focus on agricultural management to address sustainability issues [48]. Transformations in agricultural systems are essential for both environmental sustainability and global food security [19]. Food security is a priority, but there is a need for further research to understand the interactions and systems supporting it. Soil security, a lesser-known topic, is crucial for ensuring food production, highlighting the interconnectedness of agriculture and food security [61]. The seven existential threats facing human survival, including food security, climate change, water security, energy sustainability, biodiversity protection, and ecosystem services, are interrelated challenges that require integrated solutions [7].

Optimizing land management based on soil capacity reduces the need for human intervention and inputs, but political and commercial decisions often override optimal land management. A concentrated effort by individuals, organizations, and governments is necessary to transition to sustainable land use practices [55]. Conventional agriculture, facing criticism for its environmental impacts, has seen alternative methods emerge since the 1970s and 80 s, emphasizing the importance of regeneration for improving the current environmental situation [51]. Sustainability alone is insufficient; regeneration is needed to address the significant harm to the planet [29].

The foundation of regenerative agriculture is built on agricultural methods whose main goal is to regenerate soils, or raise their organic content to promote fertility. By preserving the habitats of micro- and macro-organisms, this model preserves and replenishes soil organic matter. Improved soil water conservation and erosion resistance are additional advantages [61]. The relevance of the topic—regenerative agriculture is a new trend in global development for the entire mankind. Urbanization and technology have brought a lot of environmental, social and economic problems and the world has been confronted by shortage of food and this points to the several obvious anomalies such as poverty, hunger, poor quality foods, environmental degradation, and overdependence on fertilization [61]. The Rodale Institute is a trailblazer in the field of regenerative agriculture, with Robert Rodale coining the term ‘regenerative’ to differentiate it from conventional ‘sustainable’ farming [62]. In this approach, agricultural systems not only sustain but actively enhance the resources they utilize, in contrast to depleting or consuming them. It is an all-encompassing systems-based method of farming that promotes ongoing innovation for the sake of the environment, society, economy, and spiritual wellbeing. It is quite similar to the idea of organic. Regeneration goes beyond sustainability, which ensures meeting current needs without compromising future generations [58]. Regenerative agriculture employs technology to enhance soil quality and revive the environment, focusing on increasing organic matter in the soil. This not only improves water retention but also enhances resilience to extreme weather events [61].

This article delves into current trends in the scientific exploration of the links between regenerative agriculture and food. By highlighting future research directions and transdisciplinary opportunities, it aims to lay the groundwork for securing both food and soil. Sustainable soil function, crucial for 95% of global food production, remains vital for human progress. Embracing regenerative practices becomes imperative, implicitly driving the regeneration of soils, forests, watercourses, and the atmosphere [55].

2 Food Security

The simultaneous rise in global population, incomes, and purchasing power has escalated the demand for food, fiber, and energy, necessitating increased agricultural production. The long-term pursuit of sustained food security remains, with questions arising about the sustainability of agricultural production systems, especially in emerging nations [43]. According to Pretty [56], the regenerative landscape and systems approach adopted by agricultural innovators align with all four fundamental criteria for agricultural sustainability.

These criteria involve (i) integrating ecological and biological processes into food production, such as nutrient cycling, nitrogen fixation, and soil regeneration; (ii) minimizing the use of non-renewable inputs, particularly those harmful to the ecosystem and human well-being; (iii) maximizing farmers' knowledge and skills to enhance independence and reduce reliance on external inputs; and (iv) leveraging collective abilities to address shared agricultural and resource challenges [56]. Regenerative agriculture goes beyond mere sustainability; it involves an active reconstruction or regeneration of existing systems, including landscapes and socio-ecological systems. This ongoing process aims at continual improvement, covering aspects like soil and fertility recovery, biodiversity enhancement, toxin reduction, aquifer revival, healthier food production, reduced external inputs, and the development of social capital and environmental knowledge [5]. Alexandratos [1] contends that sustainable agricultural techniques must meet the current population's food and fiber needs without compromising future generations' access to resources. The World Food Programme (WFP) emphasizes the urgency of addressing hunger and malnutrition, asserting that it poses a greater threat than AIDS, malaria, and tuberculosis combined [25]. The global population's projected increase to over 10 billion by 2050 raises concerns about doubling agricultural production, posing an unsustainable trajectory [84].

Considering the assurance of necessary nutrients for human life, the inability of families to provide sufficient food is analyzed. As agriculture faces the challenge of doubling food output, depletion of resources and ecosystem services adds complexity [73]. Agriculture, utilizing ecosystems for services like pollination and nutrient cycling, also brings about disservices, intensifying as techniques become more intensive [21, 42]. Agriculture currently occupies about 38% of the Earth's terrestrial surface, with livestock pasturelands covering approximately 26% of ice-free areas [19, 40]. The Green Revolution's productivity improvements plateaued by 1987, and human population growth outpaced food supply, resulting in over one in seven people experiencing chronic undernourishment [48, 73]. Foley et al. [19] stress the need for significant changes in agricultural consumption patterns to double production and meet anticipated demands. Regenerative agriculture, as articulated by Robert Rodale, focuses on enhancing productivity and increasing the biological production base of land and soil [62]. Aligning the food and agricultural sector with the Sustainable Development Goals (SDGs) and the Paris Climate Agreement can address the interplay of environmental, nutritional, social, and governance factors [61].

A growing population, changing climate, and environmental factors make sustaining food security challenging over time [44]. Food security involves access to enough safe and nourishing food, considering both quality and quantity [30]. Availability, access, use, and stability are distinct facets of food and nutrition security, requiring global policies for protection against societal, environmental, and political change [77]. Transitioning to productive and regenerative agriculture can positively impact food and land-use systems, enhancing yields, biodiversity, soil richness, water management, and ecosystem services [64]. However, this shift necessitates a deeper understanding and application of suitable agronomic solutions.

3 Regenerative Agriculture

Agriculture, a broad term encompassing the breeding and cultivation of living organisms for food and other purposes, includes animals, fungi, and plants. This practice provides not only sustenance but also therapeutic plants, fiber, and biofuels. The modern concept of "industrial agriculture" predominantly relies on large-scale monoculture farming, recognized as unsustainable in the long term due to inherent challenges. While one-third of the global workforce is engaged in the food production industry, this proportion is notably lower in developed countries [61].

Regenerative agriculture emerges as an alternative food production method believed by proponents to have potentially lower or even net-positive effects on ecosystems and society. Recently, stakeholders such as producers, retailers, researchers, consumers, lawmakers, and the general public have focused extensively on regenerative agriculture. Despite the attention, the term lacks a universally agreed-upon meaning in usage and lacks a legal or regulatory definition [48].

Rhodes [61] asserts that the fundamental goal of regenerative agriculture is to enhance soil health or restore severely degraded soil, thereby symbiotically improving water quality, vegetation, and land yield. According to Project Drawdown, regenerative annual cropping is projected to reduce or sequester 14.5–22 gigatons of CO2 by 2050, enhancing and sustaining soil health by restoring carbon content compared to conventional agriculture [54]. Bolder claims suggest that regenerative agriculture has the potential to reverse climate change, and a shift to "regenerative organic agriculture," characterized by widely available and affordable organic management practices, could sequester more than 100% of current annual CO2 emissions [62]. However, some critics remain cautious about how regenerative agriculture contributes to sustainability goals [45, 65]. Despite these debates, Rodale [63] contends that the objective of regenerative farming systems is to improve soil quality and biodiversity in farmland while successfully producing nutritious farm products. According to LaCanne and Lundgren [34], unifying principles that apply to all regenerative farming methods include:

1. giving up on tillage or actively reestablishing soil communities after a tillage incident,
2. removing the spatiotemporal occurrences of bare soil,
3. increasing the variety of plants on the land, and
4. combining activities for raising livestock and growing crops. Categorizing a regenerative system becomes challenging due to the myriad combinations of farming techniques employed to achieve regenerative objectives.

The comparison of conventional agriculture with alternative farming schemes often neglects the crucial aspect of the relative net profit for farmers, a key determinant in their decision-making regarding farming operations. Additionally, these comparisons fail to consider the in situ best management practices developed by farmers [13].

3.1 Disruptive Potential

A notable illustration of the ongoing transformative impact of disruption on industries beyond the conventional realm of "technology" is the potential influence of regenerative agriculture and related advancements in reshaping the landscape of farming and food production. This disruption not only presents challenges for existing, well-established players but also opens up opportunities for emerging companies and visionary investors [51]. Economic imperatives are driving substantial changes in the agricultural sector, even as the science and technology supporting many of the described methods are maturing. Indeed, the current juncture seems opportune for a complete overhaul of the prevailing practices in agriculture [9].

3.2 Technology Changing the Landscape

The regenerative strategy encompasses practices such as utilizing livestock to recycle nutrients into the soil, eliminating the need for chemical fertilizers. This approach not only yields more nutrient-rich food and enhances water retention in the soil but also provides resilience against extreme weather events intensified by climate change [9]. Furthermore, regenerative practices have the potential to mitigate various harmful externalities associated with conventional farming, including greenhouse gas emissions and the runoff of harmful chemicals into water bodies, marking a transformative shift in large-scale agriculture [33]. The expansion of regenerative agriculture aligns with the broader trend of enhancing the resilience, environmental impact, and sustainability of economic processes, making the term "sustainable" fitting.

The technological components of the regenerative approach hold significant promise for revolutionizing current agricultural practices. Biotechnological innovations, for instance, enable crops to fix nitrogen more efficiently, reducing the need for additional fertilizers and potentially cutting costs while minimizing runoff pollution and algae blooms harmful to marine life [17]. Biotechnology also presents the possibility of genetically modifying crops for enhanced drought resistance, offering solutions to improve water management in agriculture and increase yields in water-scarce conditions [27]. Although debates surround the use of genetically modified organisms, particularly concerning unintended consequences, these technologies are becoming integral, emphasizing the need for constructive discussions on their optimal utilization [81].

Similar technology-driven advancements are applicable to livestock, aiming to reduce the need for interventions with potential negative side effects. Selective breeding for disease-resistant livestock breeds, using natural selection approaches, can significantly cut expenses and externalities associated with disease treatment throughout an animal's life [11]. Since the 1980s, regenerative agriculture has consistently focused on restoring or enhancing agricultural resources to achieve sustainability. Farmers, asserting themselves as the vital link between early conceptualization and current regenerative practices, have faced academic scrutiny, although a shift in academic thought is underway, recognizing the importance of system interactions [86]. The proposed Farm-scape Function framework and the Intention, Principle, Practice, and Indicator (IPPI) mechanism provide a new approach to measure relationships between system costs, certainty, and land condition, facilitating data-driven innovation and system performance evaluation [88]. Implementing these frameworks will rely on farmers and agronomist-extension workers, fostering a situation where regenerative agriculture is defined as any system enhancing product quality and resource availability within its contextual capacity. Future research, utilizing these tools, will focus on overcoming dialogue barriers, establishing context, and cost-effectively measuring indicators, with digital agriculture expected to play a crucial role in overcoming these challenges.

4 Roles of Regenerative Agriculture

Regenerative agriculture refers to holistic farming practices that aim to produce nutrient-dense food, enhance ecosystem biodiversity, improve water and air quality, and sequester carbon to mitigate climate change effects. This approach fosters the creation of healthy soil that not only yields high-quality, nutrient-dense crops but also contributes to land improvement rather than degradation. Ultimately, regenerative agriculture strives to build productive farms, foster healthy communities, and promote thriving economies [35]. The concept of sustainable regenerative agriculture represents a radical shift, implying the adoption of significantly new tools and methodologies by farmers, according to a comprehensive meta-analysis titled "Contributions of the Land Sector to a 1.5 °C World" [75, 80]. Cropland sequestration alone is projected to reach 1.5 GtCO2/yr globally, excluding additional techniques like composting, tree cropping, hedgerows, pasture restoration, or biochar usage, which could further enhance carbon removal from arable land [36, 70].

Regenerative agriculture holds immense potential in combating climate change, with a diverse range of practices adaptable to specific regions and crop types, capable of removing 100–200 GtCO2 by the end of the century. Various frameworks and provisional definitions are proposed to guide regenerative agriculture studies [27, 68]. While some emphasize soil health as the core focus for addressing climate change, land quality, productivity, and biodiversity [68], others argue that regenerative agriculture should prioritize human factors and societal concerns. Economic perspectives are also prevalent, with proponents contending that regenerative agriculture offers "win-wins" by enhancing on-farm profits and promoting ecosystem services [34]. Alternatively, there's a viewpoint advocating for addressing social justice issues and rectifying the extractive legacy of colonial policies as prerequisites for regenerative agriculture to fulfill its promises in combating climate change [18, 34, 67].

The impact of the livestock industry on climate change, biodiversity loss, and animal welfare is widely acknowledged [80]. This situation is exacerbated by the consensus that current trends contribute to adverse health outcomes, including increased rates of non-communicable diseases, disparities in food access, and escalating risks of antibiotic resistance [14, 74, 78]. To truly establish regenerative agro-food systems, addressing industrial livestock farming and moving towards demeatification becomes imperative. Agricultural systems have evolved with changing social, environmental, and technological dynamics, presenting an opportunity for transformation. The historical role of domesticated animals in agrarian development underscores the need for reshaping interspecies relations. Challenging existing norms and adopting an ethic of care and multispecies flourishing can drive radical social change, emphasizing abundance defined by principles beyond mere growth, profits, and accumulation [12]. While the exact role of animals in regenerative agricultural systems remains uncertain, the drive for innovation should be guided by the ethical goal of ending cruelty and exploitation of animals.

5 Differences Between Regenerative and Sustainable Agriculture

Regenerative practices acknowledge that natural systems are presently impacted and apply management techniques to restore the system to improved productivity, in contrast to sustainable practices, which by definition aim to maintain the same, according to Gosnell et al. [28]. The aim to regenerate, or renew, the productivity and growth potential of whatever is being renewed is the primary distinction between these two words, regenerative agriculture and sustainable agriculture. The difference between regenerative and sustainable actions is how they use and handle the same tools, which are basically the same [66]. Furthermore, regenerative sustainability places the future of life at the center of all that we do and emphasizes sustainability plus, not just stopping from causing further harm and solving existing issues, but also essential interdependence that is generative [69]. However, Wilson et al. [82] distinguish between regenerative sustainability in two important ways:

- First, it placed emphasis on achieving net beneficial results for human and environmental wellbeing, as opposed to merely minimizing harm or doing no harm. Or, to put it another way, it queries whether our actions can enhance both environmental quality and personal wellbeing.
- Second, it recognizes the interdependence of environmental and human wellbeing, giving equal weight to both aspects.

Additionally, the goal of the discipline of regenerative medicine is to speed up the healing or regeneration of damaged organs or tissues. Some tissues in humans can naturally regenerate, including the liver, which can re-grow to its original size and function after being injured or diseased but not to its original form [50]. When used in regenerative medicine, stem cells must come from a specific source, and after being implanted, they must comprehend, engage with, and integrate into their new surroundings. Without the need for extensive in vivo testing, three-dimensional cell culture models enable investigation of key aspects of tissue regeneration. As a result, the composition and material attributes of tissue-engineered replacement scaffolds may be crucial in determining how well they perform in particular disease-related uses. When producing tissue replacements for particular treatment uses, the physiologic environment that is utilized for pre-implant culture is crucial [82].

5.1 Regenerative Agriculture and Food Security

Alternative methods have emerged in recent decades to address the drawbacks of traditional farming. These practices are frequently grouped together under the umbrella of sustainable agriculture, which is defined by the Food and Agriculture Organization (FAO) as "… the management and conservation of the natural resource base and the orientation of technological and institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations." Such sustainable growth preserves land, water, plant, and animal genetic resources and is technically sound, economically viable, and socially acceptable [10, 21]. But a number of strategies have been created and put into practice to bring about this change. The conservation tillage method, which was developed as a response to the "Dust Bowl" that impacted the US and Canadian prairies in the 1930s, is one well-established strategy [32, 87]. Conservation agriculture is another. Intercropping and crop rotation were two practices that complemented this strategy in the 1970s and 1980s. Since the 1990s, conservation agriculture has been extensively used to describe this strategy.

The FAO has highlighted three important conservation agriculture principles: minimizing soil disturbances, enhancing or maintaining a protective organic cover, and cultivating a variety of plant species^{22}. The ability of conservation agriculture to slow down and even reverse soil deterioration and restore soil quality has been demonstrated over time. Nevertheless, yields can be lower in the first few years and will only increase if certain conditions are fulfilled [53]. The use of expensive artificial fertilizer is reduced, and conservation agriculture is more resilient to anthropogenic climate change than conventional farming. These are just a few of the benefits of conservation agriculture, which also includes a reduction in the use of machinery and savings in fuel consumption [46]. The use of insecticides and herbicides can be decreased by applying conservation agriculture's three main principles wisely; in this regard, the selection of cover crops and crop rotations is crucial [10, 49]. Conservation agriculture may be able to lessen the pressure on various planetary boundaries, particularly those for freshwater and biogeochemical flows, as a result of these beneficial impacts. Many other sustainable agricultural methods have their roots in conservation agriculture, as does regenerative agriculture, which was created in the 1980s and shares many of the same concepts for soil health as conservation agriculture. The use of pesticides and herbicides, for instance, is strictly regulated in regenerative agriculture and limited to a minimum. Where regenerative agriculture differs from conventional agriculture is in its wider emphasis on boosting biodiversity in general and establishing a closed nutrient cycle in conjunction with farm-level livestock management. It also incorporates other strategies for managing grasslands, such as waste composting, rotational grazing, and silvopasture [71]. The words "conservation agriculture" and "regenerative agriculture" are frequently used interchangeably in practice because they both involve similar cropping systems. According to Müller [47], some researchers and practitioners also attribute a societal component to regenerative agriculture. Some of the more all-encompassing regenerative techniques go beyond soil renewal and also target the "regeneration" of agricultural society. For instance, in terms of satisfying employment, social connections, secure incomes, prospects for the future, and (re)establishing connections with nature [10].

5.2 Effects of Regenerative Agriculture Biophysically

The root zone of the soil is particularly moist in soils, increasing the amount of water accessible to the plants. Water uptake causes an increase in transpiration as well, and the rates are even greater when crops are grown in a particular region. Because of this, the overall effect on soil moisture varies based on the local weather, though most areas do experience higher soil moisture that is available to plants. In the comparison between the "Giant Leap" and "Too Little Too Late," a notable increase in root-zone soil moisture, approximately 4.3% across all lands, was observed. This makes conservation agriculture an effective strategy, particularly in areas where the Green Water Planetary limit has been exceeded, as indicated by deviations from dry baselines [79]. Simulations also project significant shifts in carbon and water fluxes.

The absence of soil turnover and a consistent soil cover result in less soil exposure to the atmosphere, reducing carbon oxidation and CO2 release. The additional biomass from crop residue and litter tips the balance toward a transient accumulation of soil organic carbon. Notably, these increases are prominent in tropical regions and heavily cultivated areas, such as the eastern United States, India, or Eastern China. The cumulative carbon sequestration under the "Giant Leap" scenario is estimated to reach around 26 GtC globally by 2035. A rise in soil carbon induces various changes in the soil, serving as an indicator of increased micro- and macroorganism growth, along with overall enhancements in water retention (a secondary benefit of increased root-zone soil moisture) [75]. Soil biodiversity expands due to the unaltered natural soil structure and the long-term growth of naturally occurring soil organic matter in no-till conditions [52]. These factors collectively contribute to improved ecological resilience, especially in the context of climate change [46]. Augmenting soil fertility becomes crucial for compensating for reduced yields resulting from non-tillage, especially in the initial years and humid regions. While these simulations don't consider the long-term effects of climate change, it's reasonable to anticipate that a more resilient land-use system will perform better under more extreme climate conditions [31, 85]. While cover crop implementation may not replicate the process of fixing more atmospheric nitrogen and making it available to plants at the beginning of the main season, the overall global impact is positive, with a net yield increase of approximately 5%. This is primarily evident in dry regions like the western United States, Spain, or South Africa, demonstrating that regenerative agriculture exhibits higher resilience to drought-related stresses possibly induced by climate change.

6 Conclusion

This study comes at a time of growing apprehension regarding global food security. The urgency of this matter underscores the necessity for revolutionary and transformative approaches in mindset, values, and perspectives. Given its pivotal role in sustaining humanity, agriculture is poised to play a central role in addressing food shortages. It is both a part of the predicament and a potential solution. Across diverse agricultural landscapes, transformative practices are swiftly emerging, facilitated by intricate knowledge-sharing networks. These practices are instigating substantial systemic changes and generating ample, nutritious food while concurrently rejuvenating landscapes and ecosystems.

The core of food security is intricately linked to the soil. Attempting to meet escalating food demands through unsustainable intensification is depleting the soil, and available arable land is dwindling. To avert further degradation, land use must align with its inherent capabilities. Caring for the soil and adopting measures to preserve its capacity or restore lost fertility through regenerative agriculture is imperative. Agricultural landscapes face pressure due to population shifts and suburbanization, leading to declines in agricultural land. In response, various stakeholders are exploring sustainable food production methods.

The significance of this review lies in identifying a shift in mindset and proposing mechanisms to enact it. It reinforces that the future of humanity lies in the space within our minds. This transformation in the Western mindset holds broader applications in a society undergoing radical change. Acknowledging everyone's right to be free from hunger, the ICESCR emphasizes action to enhance food production methods, spread nutritional awareness, and reform agrarian systems.

An imperative alternative to conventional agriculture is needed, marked by a departure from mainstream practices towards organic agriculture and other transformative methods. Regenerative agriculture, an encompassing approach, combines proven techniques to enhance soil quality and agricultural biodiversity. Consumer and management choices are influenced by perceptions of the soil, with education playing a crucial role. Soil health directly impacts food security, and the well-being of vulnerable subsistence farmers is intricately tied to soil conditions. Soil security components are well-defined, but more research is needed on potential connectivity indicators.

The intricate interplay of a region's natural environment, socioeconomics, and political climate shapes its agricultural systems. There's no one-size-fits-all solution, demanding exploration of alternative approaches and innovation. Soil resource management can still sustain the growing population through various techniques, such as sustainable intensification, circularization, and digital agriculture. These approaches aim to maximize crop output, repurpose land, and utilize technology to monitor and manage agricultural systems effectively.

This article underscores the interconnectedness of food security and soil security, emphasizing the need for creative thinking and collaboration. Defining indicators for food security or exploring soil security as a proxy measure is crucial. Optimal management approaches for regenerative agriculture should be based on soil conditions. Incentives and government support are essential for promoting sustainable land management practices, requiring collaboration among farmers, scientists, and the government. Clear communication of outcomes and ambiguity is needed to inform decision-makers and promote modern technologies. Integrating soil security into global projects and policies can highlight its vital role in ensuring food security, necessitating collaboration among land managers, scientists, and policymakers.

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Soil Regeneration and Microbial Community on Terrestrial Food Chain

A. I. Gabasawa, G. A. Abubakar, and D. N. Obemah

Abstract The chapter on soil regeneration explores the various methods and techniques used to restore and improve the health of soil. It delves into the importance of soil regeneration for sustainable agriculture, environmental conservation, and climate change mitigation. The chapter also discusses the detrimental effects of such conventional agricultural practices as intensive tillage, chemical fertilizers, and pesticides on soil health and biodiversity. It highlights the need for regenerative practices that focus on building organic matter, enhancing soil structure, promoting microbial activity, and increasing nutrient availability.

Keywords Soil health · Soil microbial community · Soil regeneration · Terrestrial food chain

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1 Introduction

1.1 Background and Significance of the Chapter

Soil regeneration and the microbial community are integral components of the terrestrial food chain [1–3]. Soil regeneration practices aim to restore soil health, enhance nutrient availability, improve water retention, sequester carbon, and conserve biodiversity. The microbial community [4, 5], on the other hand, plays a vital role in nutrient cycling, disease suppression, soil structure formation, and plant growth promotion. By understanding their background and significance, we can better appreciate their importance in sustaining healthy ecosystems and ensuring food security [6]. Soil regeneration and the microbial community play a crucial role in the terrestrial food chain [5, 7]. To understand their significance, it is important to delve into their background and explore how they contribute to the overall health and productivity of ecosystems.

1.2 Background of Soil Regeneration

Soil regeneration refers to the process of restoring and improving the health and fertility of soil. Over time, soil can become depleted of essential nutrients, organic matter, and beneficial microorganisms due to factors such as intensive agriculture, deforestation, pollution, erosion, and climate change. This degradation of soil quality can have detrimental effects on plant growth, crop yields, and overall ecosystem functioning. Soil regeneration aims to reverse these negative impacts by implementing sustainable practices that enhance soil health and restore its natural balance. This involves replenishing organic matter, improving soil structure, promoting nutrient cycling, and fostering a diverse microbial community [5]. By rejuvenating the soil, it becomes more resilient to environmental stresses and supports the growth of healthy plants.

1.3 Significance of Soil Regeneration

Soil regeneration is of paramount importance for several reasons, including the following:

Enhanced Nutrient Availability

Healthy soils are rich in nutrients that are essential for plant growth. Through soil regeneration practices such as composting, cover cropping, and crop rotation, organic matter is added to the soil, which improves nutrient availability. This leads to increased plant productivity and higher crop yields.

Water Retention and Filtration

Regenerated soils have improved water-holding capacity, allowing them to retain moisture for longer periods. This is particularly important in arid or regions that are vulnerable to drought due to water scarcity. Furthermore, healthy soils play natural filter roles by removing pollutants/contaminants from water as it percolates through the soil profile.

Carbon Sequestration

Soil plays a significant role in carbon sequestration, which helps in mitigating climate change by reducing greenhouse gas emissions [8, 9]. Regenerating soil increases its organic matter content [5], which in turn enhances carbon storage. This process, known as soil carbon sequestration, helps to offset carbon dioxide emissions and contributes to the global effort of reducing atmospheric greenhouse gas concentrations [11].

Biodiversity Conservation

Soil regeneration promotes biodiversity by creating a favorable habitat for a wide range of organisms [2, 3]. Microorganisms, fungi, earthworms, and other soil-borne organisms thrive in healthy soils and contribute to nutrient cycling, organic matter decomposition, and disease suppression. This biodiversity is essential for maintaining ecosystem resilience and stability [5, 12].

1.4 Background of Microbial Community

The microbial community refers to the diverse array of microorganisms that inhabit the soil environment [12]. These microorganisms include bacteria, fungi, archaea, viruses, and protozoa. They play a crucial role in various soil processes and have a profound impact on the terrestrial food chain. Microbes in the soil interact with plants in a symbiotic relationship. They form associations with plant roots known as mycorrhizae, where they exchange nutrients with the host plant. This mutualistic relationship enhances nutrient uptake by plants, particularly phosphorus and nitrogen, which are often limited in soil.

1.5 Significance of Microbial Community

The soil microbial community has several significant roles which include, although not limited to the following [4, 5, 11]:

Nutrient Cycling

Microbes are key players in nutrient cycling processes such as decomposition and mineralization. They break down organic matter into simpler forms, releasing nutrients that can be assimilated by plants. This cycling of nutrients is essential for sustaining plant growth and productivity [5].

Disease Suppression

Certain soil microorganisms have the capability of suppressing plant diseases that are caused by pathogens. They do so through various mechanisms such as competition for resources, production of antimicrobial compounds, and induction of systemic resistance in plants. A diverse and healthy microbial community can help protect crops from diseases and reduce the reliance on chemical pesticides.

Soil Structure and Aggregation

Microorganisms contribute to the formation and stabilization of soil aggregates, which improve soil structure. Soil aggregates provide pore spaces for air and water movements, root penetration, and habitat for soil organisms. They also help in preventing soil erosion by reducing surface runoff and enhancing water infiltration.

Plant Growth Promotion

Some microbes have the capacity of stimulating plant growth through the production of growth-promoting substances such as phytohormones. They can also enhance nutrient availability by solubilizing minerals and fixing atmospheric nitrogen (N_2). These beneficial interactions between microbes and plants contribute to increased crop yields and overall plant health.

1.6 Objectives of the Chapter

The broad objective this chapter is to provide an insight on the role of soil regeneration and microbial communities in sustaining and enhancing the productivity and health of the terrestrial food chain. An exploration into the intricate relationship between soil, microorganisms, and plants, highlighting their crucial roles in nutrient cycling, organic matter decomposition, plant growth promotion, disease suppression, and overall ecosystem functioning is another aspect of that. Specifically, however, the chapter sought to: (1) understand the importance of soil regeneration and microbial communities in the terrestrial food chain (2) learn the different types of soil regeneration techniques and their effects on microbial communities (3) explore the role of microbial communities in the terrestrial food chain (4) understand the impact of human activities on soil regeneration and microbial communities and (5) learn about sustainable land management practices that promote soil regeneration and microbial communities.

2 Soil Regeneration

2.1 Definition and Importance of Soil Regeneration

Soil regeneration refers to the process of restoring and revitalizing the health and fertility of soil [1–3]. It involves enhancing the physical, chemical, and biological properties of such soil to create a favorable environment for plant growth and nutrient cycling. One crucial aspect of soil regeneration is the promotion of a diverse and thriving microbial community [4] which plays a fundamental role in the terrestrial food chain for being responsible for various essential functions in soil ecosystems [2, 3].

2.2 Factors Influencing Soil Regeneration

Soil regeneration is a complex process that is influenced by diverse factors that interact with each other to determine the health and fertility of the soil [3]. These factors can be broadly categorized into physical, chemical, and biological aspects. Understanding these factors is crucial for sustainable agriculture and land management practices.

A. Physical Factors

Soil Structure: The arrangement of soil particles affects water infiltration, root penetration, and air circulation within the soil. A well-structured soil with good aggregation allows for better nutrient availability and root development.

Soil Texture: Soil texture refers to the relative proportions of sand, silt, and clay particles in the soil. Different textures have varying water-holding capacities, drainage abilities, and nutrient retention capacities.

Compaction: Soil compaction occurs when excessive pressure is applied to the soil, leading to reduced pore space and restricted root growth. Compacted soils have poor water infiltration rates and limited oxygen availability for plant roots.

B. Chemical Factors

Soil reaction (pH): Soil pH influences nutrient availability as it affects the solubility and mobility of essential elements. Different plants have specific pH requirements for optimal growth.

Nutrient Content: The presence and balance of essential nutrients like N, P, K, Ca, Mg, and micronutrients are crucial for plant growth. Nutrient deficiencies or imbalances can hinder soil regeneration.

Organic Matter: Organic matter plays a vital role in soil regeneration by improving soil structure, water-holding capacity, nutrient retention, and microbial activity. It also acts as a source of slow-release nutrients.

C. Biological Factors

Microorganisms: Soil microorganisms such as bacteria, fungi, protozoa, nematodes, and earthworms play a crucial role in nutrient cycling, organic matter decomposition, disease suppression, and soil structure formation.

Plant Diversity: Different plant species have varying root structures and exudates, which influence soil microbial communities and nutrient cycling processes. A diverse plant community can enhance soil regeneration by promoting beneficial interactions between plants and microorganisms.

Cover Crops: Planting cover crops during fallow periods helps prevent soil erosion, improves organic matter content, fixes nitrogen, and enhances soil structure. Cover crops also provide habitat for beneficial insects and suppress weeds.

Other factors that can influence soil regeneration include climate (temperature and precipitation patterns), topography (slope and aspect), land management practices (tillage, crop rotation, irrigation), and the presence of pollutants or contaminants.

3 Microbial Community in Soils

Soil microbial community is a complex network of microorganisms that play a vital role in various soil processes [7]. Bacteria, fungi, archaea, viruses, and other microorganisms interact with each other and with plants to maintain soil health and fertility. Understanding the composition and function of these microorganisms is crucial for sustainable land management practices [3]. Proper understanding of the community is also essential for sustainable agriculture and environmental management the study of the composition and function of which can assist scientists to develop strategies that will see to soil fertility enhancement, crop productivity improvement, and mitigation of such environmental maladies as nutrient losses and soil erosion.

3.1 Introduction to Soil Microbial Community

The soil microbial community refers to the diverse population of microorganisms that inhabit the soil environment [4, 9]. The soil microbial community plays a crucial role in maintaining soil health and fertility. Soil microorganisms are involved in nutrient cycling, organic matter decomposition, disease suppression, and plant growth promotion. They also contribute to the formation and stabilization of soil aggregates, which improve soil structure and water infiltration. Furthermore, the microbial community helps in the detoxification of pollutants and the degradation of organic contaminants in soils [7].

3.2 Types of Soil Microorganisms

These microorganisms include bacteria, fungi, archaea, viruses, and other microscopic organisms. They play a crucial role in various soil processes and have a significant impact on soil health and fertility.

A. Bacteria
Bacteria are one of the most abundant and diverse groups of microorganisms in the soil microbial community. They are responsible for numerous essential functions in the soil ecosystem. Some bacteria are involved in nutrient cycling, such as nitrogen fixation [7, 12, 13], where they convert atmospheric nitrogen into a form that plants can use. Others are involved in organic matter decomposition, breaking down complex organic compounds into simpler forms that can be taken up by plants. Additionally, certain bacteria can suppress plant pathogens and promote plant growth through the production of growth-promoting substances.

B. Fungi
Fungi are another important group of microorganisms in the soil microbial community. They play a crucial role in organic matter decomposition and nutrient cycling [8, 14]. Fungi break down complex organic compounds, such as *lignin* and *cellulose*, into simpler forms, releasing nutrients back into the soil. They also form mutualistic associations with plant roots, known as mycorrhizae, where they provide plants with nutrients in exchange for carbon compounds produced by the plants. This symbiotic relationship enhances plant nutrient uptake and improves plant resilience to environmental stresses.

C. Archaea
Archaea are single-celled microorganisms that were initially classified as bacteria but now recognized as a distinct domain of life. They are found in various environments, including soil. Archaea have diverse metabolic capabilities and can thrive in extreme conditions such as high temperatures, salinity, or low oxygen levels and can also be found in various soil habitats. In the soil, archaea contribute to nutrient cycling processes, particularly nitrogen cycling and methane production and consumption. Although less well-studied when compared to bacteria and fungi, archaea (Table 1) also contribute to the soil microbial community.

D. Viruses
Although not technically considered as living organisms, viruses, are abundant in soils and have a significant impact on microbial communities. Soil viruses infect bacteria, fungi, archaea, and other microorganisms, thereby influencing their abundance and diversity. Viruses can control microbial populations by lysing infected cells and consequently releasing nutrients back into the soil.

E. Protozoa
Protozoa are unicellular eukaryotic organisms that inhabit the soil environment. They play a vital role in regulating bacterial populations through predation, thereby influencing microbial community structure and nutrient cycling dynamics. Protozoa consume bacteria and release excess nutrients through their

Table 1 Soil organisms: types and functions in soils

S/ no	Type of soil organism	Function/Activity in soil	References
1	Bacteria: *Azospirillum, Rhizobia, Pseudomonas, Bacillus, Azotobacter*	Ingested by earthworms and increase their population. They solubilize un-available nutrients into available, produce extra-enzyme used for plant growth promoting hormones and keep the soil fertile and healthy. They are important in producing polysaccharides that cement sand, silt and clay particles together to form micro-aggregates and improve soil structure A coating of polysaccharides or glycol proteins that coats the surface of soil particles is formed by many bacteria. Bacteria degrade pesticides through mineralization and co-metabolisms through breakdown or transformation of complex substrates into simpler products. They degrade pesticides	[34–38]
2	Fungi: *Ascomycetes* *Basidiomycetes* *Zygomycetes* *Glomeromycetes* *Chytridiomycetes* *Deuteromycetes* (Fungi *Imperfecti*) *Oomycetes*	Fungus plays a central role in soil fertility, processing, promoting crops health and involved in soil organic matter (SOM) protection. They also play vital role in the stabilization of SOM, immobilization, nutrients retention, and decomposition of residues in the soil, so it is also very essential to maintain fungal biodiversity in soil. Fungi have a profound influence on biogeochemical cycles through their growth habits, which include external digestion of food resources by their digestive enzymes, and secondary metabolites. The rate of turnover of fungal biomass has significant consequences for the C cycle and long-term sequestration in soil. Fungi dominate microbial biomass and activity in soil organic horizons mainly in the forest, and they are mainly influenced by N and P	[39–45]

(continued)

Table 1 (continued)

S/ no	Type of soil organism	Function/Activity in soil	References
3	Archaea: *Euryarchaeota* *Euryarchaeota,* *Crenarchaeota* *Methanogens* *Crenarchaeota* *Euryarchaeota* *Thaumarchaeota* *Crenarchaeota* *Euryarchaeota* *Crenarchaeota* *Euryarchaeota* *Nitrosopumilus* *Nitrososphaera* *Nitrosocosmicusoleophilus MY3* *Crenarchaeota* *Euryarchaeota* *Methanobacterium Methanoregula* *Methanospirillum Methanomethylovorans* *Methanosarcina* *Methanosaeta* *Crenarchaeota Thaumarchaeota Euryarchaeota* *Crenarchaeota* *Methanosarcina Methanocellales* *Methanosaetaceae Thaumarchaeota Halobacteria* *Methanobacteria Methanomicrobia Thermoprotei* *Methanobacteriales Methanosarcinales* *Methanocellales*	Archaea are a significant division of life forms, abundant in both severe and normal habitats. Little attention has been paid to them as an integrated component of various metabolic processes of the plant microbiome. The employment of these microorganisms in agriculture replacing, or at least, decreasing the input of chemical fertilizers is one of the most important proposals for sustainable agriculture particularly for non-leguminous plants. Plants cannot directly utilize N that is freely available in the atmosphere (N_2). Like bacteria however, certain archaea can convert the N_2 into ammonia (NH_4), the plant-utilizable form for diverse biological processes. Archaea are being given a special attention as a potential plant growth-promoter (PGPA). Also, Ammonia-oxidizing archaea (AOA), like its ammonia-oxidizing bacteria (AOB), is also a key driver of nitrification in rain-fed soil ecosystems. They can thrive under such extreme conditions as moisture-deficient saline regimes plus their ability to affect plant growth through phosphate solubilisation that makes them good potential biotechnological candidates for plant growth promotion particularly for their adaptability to various ecosystems. Many strains of Archaea exist in the rhizosphere of different plants	[38, 46–49]

(continued)

Table 1 (continued)

S/ no	Type of soil organism	Function/Activity in soil	References
4	Viruses: *Caudovirales* *Microviridae* *Inoviridae* *Leviviridae* *Geminiviridae* *Narnaviridae* *Partitiviridae* *Chrysoviridae* *Totiviridae* *Bunyavirales (Hantaviridae Phenuiviridae)*	Viruses could regulate dynamics of bacterial community composition through their lysing activities, and through the associated changes in substrate availability. Lytic activities of soil viruses may further affect substrate availability. This, in turn, influences subsequent community succession. Viruses mediate the conversion of particulate organic matter (POM) into dissolved organic matter (DOM) through lysing of the host cells, which is also known as the "viral shunt". Soil viruses could also mediate the flow of organic carbon from DOM to POM. Here, these C- and N-rich POMs persisted during the course of experiment, indicating relatively low bioavailability	[50–62]
5	Protozoa: *Amoebae* *Flagellates* *Ciliates* *Testate Amoebae* *Heliozoa* (Sun *Animalcules)*	Protozoa are unicellular, eukaryote organisms, first surveyed and described by Anthonie van Leeuwenhoek (1632–1723) who called them animalicules or 'little animals' after developing a primitive microscope. The microorganisms are the smallest but most numerous of all animals. Although protozoan taxonomy is still debatable, several ten thousands of species have been described. Protozoa as microbivore, after grazing on microbes the nutrients immobilized in microbial biomass are eventually mineralized and released. They can be responsible for a significant portion of the mineralization of nitrogen in soils	[35, 45, 63–65]
6	Nematodes: *Secernentea (Rhabditida, Strongylida, Tylenchida)* *Adenophorea (Dorylaimida)* *Chromadorea (Mononchida)* *Enoplea (Triplonchida)* *Chromadoria (Desmodorida)*	Nematodes, multicellular, aquatic organisms that inhabit water films surrounding soil particles are amongst the most widely used bioindicator groups of soil ecosystems. They are useful in measuring changes in the function and status of soils, for their ubiquitous distribution and occupation of a wide range of habitats; and being representative of multiple trophic levels in the soil food web. They also reflect changes in terrestrial habitats due to their rapid response to environmental and anthropogenic disturbances. They are considered valuable indicators of soil ecosystem health. After grazing on microorganisms, nematodes like their protozoa microbivores counterparts, mineralize the immobilized nutrients into microbial biomass and release the same	[35, 63, 64, 66–73]

(continued)

Table 1 (continued)

S/ no	Type of soil organism	Function/Activity in soil	References
7	Algae: *Bacillariophyceae* (green algae: *Spirogyra* and *Zygnema*) *Chlorophyceae* (green algae: *Scenedesmus* and *Chlorococcum*) *Cyanobacteria* (Blue-green algae: *Oscillatoria* and *Microcystis*) *Diatomeae* (diatoms: *Navicula* and *Fragillaria*) *Euglenophyceae* (*euglenids*: *Euaglenes* and Heter Euglena) *Xanthophyceae* (yellow-green algae: *Vaucheria* and *Rhodophora*) *Cyanophyta*: (*Chroococcus minimus*, *Ch. minutus*, *Ch. varius*, *Gloeocapsa atrata*, *Merismopedia glauca*, *Synechococcus aeruginosus, Nostoc commune, Oscillatoria* sp. and *Phormidium* sp.); *Heterokontophyta*: (*Pinnularia borealis*); *Chlorophyta*: (*Stichococcus chlorelloides*, S. cf. *fragilis*, *Hormidiopsis crenulata*, *Cylindrocapsa* sp. and *Ulothrix* sp.) *Synechococcus aeruginosus*, (*H. crenualtum*, *Cylindrocapsa* sp., *Osillatoria* sp. and *Phormidum* sp.)	They are a diverse group of aquatic organisms capable of photosynthesising. Some of them like seaweeds (*e.g.*, kelp or phytoplankton), pond scum or algal blooms in lakes) are known by many people. There, however, exists a vast and diverse other types that are variously helpful even to humans. Soil algae play important roles in all soil development stages. Ecologically diverse groups of algae participate in many processes at different stages. Their influence is more glaring at the initial stage of soil formation, *i.e.*, during the colonization of an abiotic ground and the formation of a primary layer enriched in organic C on this mineral substrate. Almost up to the present, this role has been ascribed to *lichens*. Autotrophic algae are capable of producing and accumulating organic matter and, hence, stimulates the development of heterotrophic organisms. They initiate biochemical processes in the soil environment. This results in the release N P. K, Ca, Mg and other microelements from mineral substances. Algae are very significant to soil formation in both arid and semiarid regions, and in moderate climate zones, both in natural and anthropogenic ecosystems. Their participation in primitive soil formation, particularly, in desert areas, was thoroughly explained in different works studies. As algae, lichens and lower plants form the basic biological set in arid areas, their importance and role in soil formation is better known in those environments than it is for soils in moderate climate zones, where higher plants are much more important. Soil algae generally includes the whole set of such ecologically diverse groups as (a) algae growing over the entire surface of soil and forming a crust, (b) algae living on moist soil surfaces and (c) algae occurring within the soil. Underground soil algae in arid habitats rarely occur as solitary organisms but are, more commonly, associated with fungi, lichens, club mosses and bryophytes forming continuous biological soil crusts. Though soil algae play an important role during initial pedogenesis processes, their taxonomy and occurrence has not been well described. In unstable sandy areas, organisms with higher edaphic requirements cannot survive. Algae are the first organisms to colonize areas exposed to wind erosion and metal-pollution	[74–76]

excretion, making them available for plant uptake. They also contribute to the formation and stabilization of soil aggregates, which improves soil structure and water infiltration, and consequently good plant growth and development.

F. Nematodes
Nematodes are small, worm-like organisms that can be found in soil. They are classified into various groups based on their feeding habits. Some nematodes are bacterivorous, feeding on bacteria, while others are fungivores, feeding on fungi. There are also predatory nematodes that consume other nematodes or small soil animals. Nematodes play a crucial role in nutrient cycling and decomposition processes [15]. They can influence the abundance and activity of other soil microorganisms through their feeding activities.

G. Algae
Algae are photosynthetic microorganisms that can be found in moist soils or aquatic environments within the soil ecosystem. They play a role in primary production by converting sunlight into organic matter through photosynthesis [16]. Algae (Table 1) contribute to nutrient cycling and can enhance soil fertility by fixing atmospheric nitrogen.

The composition and structure of soil microbial community are influenced by various factors [17], including soil type, climate, land management practices, and plant species. Different soils can harbor distinct microbial communities due to variations in physical and chemical properties. For instance, acidic soils may have different microbial populations compared to alkaline soils. Similarly, such agricultural practices as tillage, fertilization, and pesticide use can affect the diversity and abundance of soil microorganisms.

4 Interactions Between Soil Regeneration and Microbial Community

Soil regeneration and microbial communities have a complex and mutually beneficial relationship. The interactions between soil regeneration and microbial communities are highly interconnected and mutually beneficial [2, 3]. It also play a critical role in maintaining soil health, nutrient cycling, and overall ecosystem functioning. This will result to delving into the various aspects of this relationship, including the effects of soil regeneration on microbial communities and vice versa.

4.1 Effects of Soil Regeneration on Microbial Communities

Soil regeneration significantly affects microbial communities through the critical role that it serves in maintaining soil health, nutrient cycling, and the general ecosystem functioning, as in the following ways:

A. Increase in Microbial Diversity

Such soil regeneration practices as organic farming, cover cropping, and reduced tillage promote the growth of diverse plant species and enhance organic matter content in the soil [3, 8, 13]. These practices provide a favorable environment for a wide array of microorganisms to thrive. Increased microbial diversity is beneficial as it enhances the functional capacity of the soil ecosystem, leading to improved nutrient cycling, disease suppression, and overall soil fertility.

B. Enhanced Microbial Activity

Soil regeneration practices often involve the addition of organic amendments such as compost or manure. These amendments serve as a source of nutrients for microorganisms, stimulating their growth and activity. As a result, microbial populations increase in size and become more active in decomposing organic matter, releasing essential nutrients for plant uptake. This enhanced microbial activity contributes to improved soil structure, nutrient availability, and overall soil health.

C. Promotion of Beneficial Microorganisms

Soil regeneration practices can favor the proliferation of beneficial microorganisms such as mycorrhizal fungi and nitrogen-fixing bacteria. Mycorrhizal fungi form symbiotic associations with plant roots, facilitating nutrient uptake by plants, especially phosphorus. Nitrogen-fixing bacteria convert atmospheric nitrogen into plant-available forms, thereby reducing the need for synthetic fertilizers. By promoting these beneficial microorganisms, soil regeneration practices contribute to sustainable agriculture and reduce reliance on external inputs [3, 14].

5 Effects of Microbial Communities on Soil Regeneration

The microbial communities significantly affect, and hence, contribute to nutrient cycling, soil structure formation, and disease suppression during the process of soil regeneration.

5.1 Nutrient Cycling

Microbial communities play a vital role in nutrient cycling within the soil ecosystem. They decompose organic matter, releasing nutrients that are essential for plant growth. Microbes break down complex organic compounds into simpler forms, making them available for uptake by plants [2–4]. This nutrient cycling process is critical for maintaining soil fertility and supporting plant growth during soil regeneration.

5.2 Soil Structure Formation

Microbial communities contribute to the formation and stabilization of soil aggregates, which are crucial for maintaining good soil structure. Certain groups of microorganisms, such as fungi and bacteria, produce sticky substances called exopolysaccharides that bind soil particles together, creating stable aggregates. These aggregates improve soil porosity, water infiltration, and root penetration, ultimately enhancing soil regeneration efforts.

5.3 Disease Suppression

Some microbial communities have the ability to suppress plant diseases through various mechanisms. For example, certain bacteria and fungi produce antibiotics or enzymes that inhibit the growth of pathogenic organisms. Additionally, mycorrhizal fungi can form a protective barrier around plant roots, preventing pathogen invasion. The presence of diverse and healthy microbial communities can help suppress soil-borne diseases and promote plant health during the process of soil regeneration.

6 Influence of Soil Regeneration Practices on Microbial Community Composition and Diversity

Soil regeneration practices can have a significant impact on the microbial communities that inhabit the soil. These practices aim to improve soil health, and consequently its fertility, increase crop yields, and enhance such ecosystem services as carbon sequestration [29, 30] and nutrient cycling. However, the effects of these practices on microbial communities are not well understood. This section of the chapter will explore the influence of soil regeneration practices on microbial community, composition and diversity. Soil regeneration practices can alter a given microbial community composition and diversity through several mechanisms [7]. Such mechanisms may include, but not limited to the following.

6.1 Changes in Soil Physicochemical Properties

Soil regeneration practices can modify soil temperature, moisture, pH, and nutrient availability, which can affect microbial growth and survival. For example, increased soil organic matter due to mulching or cover cropping can improve soil structure, increase water holding capacity, and provide a more stable supply of nutrients, leading to an increase in microbial abundance and diversity.

6.2 Addition of Organic Amendments

Compost, manure, or other organic amendments can alter microbial community composition by providing a source of carbon and nutrients that favors certain microorganisms over others. For instance, adding compost can increase the abundance of fungi and *actinomycetes*, while manure can promote the growth of bacteria and protozoa.

6.3 Modification of Soil Biota

Soil regeneration practices can directly and/or indirectly affect soil biota, such as earthworms, insects, and nematodes, which can alter microbial community composition and diversity. Tillage, for example, can disrupt soil structure and reduce the abundance of earthworms [8], which can lead to changes in microbial community composition [4, 5, 17, 25].

6.4 Shifts in Vegetation Cover

Vegetation cover can influence microbial community composition and diversity by providing a source of carbon and nutrients, shading the soil, and modifying soil moisture and temperature. For example, the shift from a monoculture of corn to a polyculture of legumes and grasses can alter the composition of microbial communities and increase their diversity. Several studies have investigated the effects of soil regeneration practices on microbial community composition and diversity [18, 19]. In a study by Janssens et al. [20], for instance, it was found that addition of compost to agricultural soils increased the abundance and diversity of fungi and bacteria. In that same study by [19], on the other hand, it was found that a reduction in tillage intensity had increased the abundance of *actinomycetes* and decreased bacterial abundance of agroecosystems. Also, a study by Zhang et al. [27] discovered that converting conventional tillage to no-tillage increased fungal abundance but reduced that of bacteria in wheat–maize rotations [28].

7 Impact of Microbial Community on Soil Fertility and Nutrient Availability

The soil microbial communities, on the other hand, also play a crucial role in maintaining soil health, fertility and nutrient availability. In that, they decompose organic matter, fix atmospheric nitrogen (N_2), solubilize minerals, and produce antibiotics and other compounds that protect plants against pathogens [24]. Microorganisms also contribute to soil structure and aggregation, which affect water infiltration, aeration, and nutrient availability [31, 32]. Therefore, any changes in microbial community composition or diversity can have far-reaching consequences for soil function and ecosystem services. The impact of microbial communities on soil fertility and nutrient availability is, therefore, vital and plays an utmost role in maintaining the health and terrestrial ecosystems productivity [31, 32]. Microorganisms, including bacteria, fungi, and archaea; and even viruses, are abundant in soil and form complex interactions with plants, organic matter, and mineral components. These interactions influence various soil processes, such as nutrient cycling, organic matter decomposition, and plant–microbe interactions. Hence, the microbial communities contribute to soil fertility through several mechanisms, including.

7.1 Nutrient Cycling

Microorganisms play a vital role in the cycling of nutrients in the soil [7]. They decompose organic matter, thereby releasing essential nutrients such as N, P, and S into forms that can be readily assimilated by plants. Certain classes of bacteria and fungi, for example, convert N_2 into plant-available forms through a process called nitrogen fixation [13, 21]. Similarly, mycorrhizal fungi form symbiotic associations with plant roots, enhancing nutrient uptake, particularly phosphorus [21].

7.2 Organic Matter Decomposition

Microorganisms are key drivers of organic matter decomposition in soils. In that, they break down complex organic compounds into simpler forms through enzymatic activity. This process releases nutrients trapped within the organic matter, making them available for plant uptake. The decomposition of organic matter also contributes to the formation of stable soil aggregates, improving soil structure and water-holding capacity.

7.3 Plant–microbe Interactions

Microorganisms also interact, closely, with plants through symbiotic relationships or pathogenic interactions. Such beneficial microbes as rhizobia and mycorrhizal fungi, form mutualistic associations with plants, and provide them with nutrients while themselves receive carbon compounds from the, usually host, plants. These associations enhance plant growth and nutrient acquisition. On the other hand, the pathogenic microorganisms can cause diseases in plants that lead to reduced nutrient uptake and a consequent overall decline in soil fertility.

8 Influence of Microbial Communities on Nutrient Availability of Soils

Various microbial communities can influence the availability of nutrients in agricultural soils in various ways, such as.

8.1 Nutrient Transformation

Microorganisms mediate various nutrient transformations in the soil thereby affecting their availability to plants. Certain bacteria, for example, convert insoluble forms of P into its soluble forms through a process called phosphorus solubilization. This makes P more readily accessible to plants. Similarly, microorganisms can immobilize or mineralize N thereby affecting its availability for plant uptake.

8.2 Microbial Competition

Microbes compete for nutrients and other limited resources in the soil. This competition can influence nutrient availability by determining which microbes dominate and utilize specific nutrients. For instance, certain bacteria may outcompete plants for N thereby reducing its availability to plants.

8.3 Soil Reaction (pH) and Redox Potential

Microorganisms can influence soil pH and redox potential, which in turn affect nutrient availability. Some microbes produce organic acids during metabolic processes, leading to acidification of the soil. This acidification can enhance the release of nutrients from minerals and organic matter. More so, microbial activity can influence the redox potential of the soil to also affect the availability of some nutrients like Fe and Mn.

9 Role of Microbial Community in Promoting Plant Growth and Health

The microbial community plays a crucial role in promoting plant growth, development and health. These microorganisms, including bacteria, fungi, and archaea, form complex interactions with plants and contribute to various aspects of their development and well-being. This symbiotic relationship between plants and microbes is known as the plant microbiome [7, 8]. The plant microbiome refers to the collective microbial communities that reside on or within plants [22, 23]. It is a dynamic and diverse ecosystem that influences plant growth, nutrient acquisition, disease resistance, and overall plant health [9, 10]. The interactions between plants and their associated microbes are highly intricate and can have profound effects on plant physiology [11].

One of the key roles of the microbial community in promoting plant growth is nutrient acquisition. Microorganisms assist crop plants to access essential nutrients by breaking down complex organic matter in the soil into simpler forms that can be readily absorbed by plants. As stated earlier, certain bacteria, for example, can fix dinitrogen (N_2) into a plant-utilizable form, and hence, enhancing N availability. Similarly, mycorrhizal fungi form mutualistic associations with plant roots, extending their reach into the soil and facilitating the uptake of nutrients such as P. Microbes also contribute to disease suppression in plants. Some beneficial bacteria and fungi have the ability to produce antimicrobial compounds or compete with pathogenic organisms for resources, thereby reducing the incidence and severity of plant diseases.

These beneficial microbes can act as biocontrol agents against various pathogens, protecting plants from infections. Furthermore, the microbial community plays a role in plant hormone regulation as some microbes can produce or modulate such plant hormones as auxins, cytokinins, and gibberellins, which are involved in various aspects of plant growth and development. By influencing hormone levels or signaling pathways, microorganisms can promote root development, enhance shoot growth, stimulate flowering, and improve overall plant vigor. Additionally, the microbial community also, indirectly, contributes to soil health in many ways, as they play a crucial role in maintaining soil structure, nutrient cycling, and organic matter decomposition [26]. They help break down complex organic compounds, releasing nutrients that are essential for plant growth. Microbial activity in the soil can improve soil fertility, water-holding capacity, and resistance to erosion.

10 Feedback Mechanisms Between Soil Regeneration and Microbial Community Dynamics

Soil regeneration and microbial community dynamics are intricately linked through a variety of feedback mechanisms. These mechanisms involve the interactions between soil properties, plant roots, organic matter inputs, and the activities of microorganisms. Understanding these feedback mechanisms is crucial for sustainable agriculture and ecosystem management. One important feedback mechanism is the influence of soil properties on microbial community dynamics. Soil properties such as pH, moisture content, nutrient availability, and organic matter content play a significant role in shaping the composition and activity of microbial communities. Different microbial *taxa* have specific preferences for certain soil conditions, and changes in these conditions can tantamount to shifts in microbial community structure. For example, studies have shown that acidic soils tend to have lower microbial diversity compared to neutral or alkaline soils. This is because acidophilic microorganisms are better adapted to acidic conditions and can outcompete other *taxa*. Similarly, waterlogged anaerobic soils favor the growth of anaerobic microorganisms, while well-drained soils support a more diverse range of aerobic microorganisms.

Another feedback mechanism involves the influence of microbial communities on soil regeneration. Microorganisms play an important role in nutrient cycling and organic matter decomposition, which are essential processes for soil fertility and regeneration. They break down complex organic compounds into simpler forms that can be readily assimilated by plants. This process releases nutrients such as N, P, and S into the soil, making them available for plant uptake. Microbial communities also contribute to soil aggregation and structure formation. Some microbial groups produce sticky substances called extracellular polymeric substances (EPS), which act as a glue that binds soil particles together. This helps to create stable aggregates that improve soil structure, porosity, and water infiltration capacity. Microbial communities can indirectly influence plant growth and health through plant–microbe interactions. This is in addition to their aforesaid direct effects on soil regeneration. Some other microbes form mutualistic relationships with plants, providing them with nutrients, growth-promoting hormones, and protection against pathogens. These beneficial interactions can enhance plant productivity and resilience to environmental stresses.

Conversely however, certain microorganisms can have negative effects on plants, causing diseases or inhibiting growth. Understanding the dynamics of these plant–microbe interactions is very essential for managing soil health and optimizing agricultural practices. The feedback mechanisms between soil regeneration and microbial community dynamics are complex and dynamic, influenced by a range of factors including land management practices, climate, and plant species composition. For example, agricultural practices such as tillage, pesticide use, and synthetic fertilizer application can disrupt microbial communities and reduce soil fertility over time [25]. Sustainable land management practices that promote soil regeneration [33], such as organic farming, cover cropping, and crop rotation, can on the other hand enhance microbial diversity and activity. These practices provide a continuous supply of organic matter to the soil, which serves as a food source for microorganisms. In turn, the activities of microorganisms contribute to nutrient cycling, organic matter decomposition, and soil structure formation [14, 15].

11 Summary of Major Points

Soil regeneration is essential for maintaining soil health and fertility as it involves the amelioration of degraded soils through various practices and techniques [24, 25]. Such sustainable agricultural practices as cover cropping, crop rotation, and use of organic amendments play a vital role in soil regeneration as it can improve soil structure, nutrient availability, and water-holding capacity. Another vital role of soil regeneration is the promotion of beneficial microorganisms [24]. In that, such practices like composting and the use of microbial inoculants can judiciously enhance microbial diversity and activity in the soil. Precision agriculture and remote sensing technologies can assist in monitoring soil health parameters and guiding management decisions for effective soil regeneration. Soil conservation measures are necessary to prevent further degradation and erosion of soils [33]. Hence, employing erosion control practices such as contour plowing and terracing can help preserve topsoil. Climate change, on the other hand, poses challenges to soil regeneration efforts [2]. Nonetheless, adaption of agricultural practices based on changing climatic conditions is crucial for sustaining soil health. Collaboration between researchers, farmers, policymakers, and other stakeholders is essential for promoting soil regeneration on a larger scale. Finally, further research is needed to deepen a better understanding of the complex interactions within the soil ecosystem and develop innovative strategies for soil regeneration [3, 4].

12 A Clarion Call for Action and Future Research Directions

Amongst the most paramount needs are to investigate the long-term effects of sustainable agricultural practices on soil regeneration [14, 18, 21]. Long-term studies can provide valuable insights into the cumulative benefits and potential drawbacks of different approaches. An exploration into the role of soil microorganisms in soil regeneration is another. Understanding the interactions between microbes and soil components can help in developing targeted interventions to enhance microbial activity and diversity. Developing advanced innovative technologies for monitoring soil health parameters such as remote sensing, sensor technologies, and data analytics can enable real-time monitoring of soil conditions thereby facilitating timely management decisions. Researches on the assessment of the impact of climate change on soil regeneration processes should focus on the identification of adaptive strategies of mitigating the negative effects of climate change on soil fertility and its general health. Conducting interdisciplinary collaborative research between agronomists, ecologists, microbiologists, and other relevant disciplines will holistically address knowledge gaps in soil regeneration for an assured sustainable soil management [14, 18]. Promotion of knowledge transfer and education programs to raise awareness about the importance of soil regeneration among farmers, policymakers, and the general public cannot be over-measured. Also, encouraging policy support for sustainable agricultural practices that will promote soil regeneration practices among farmers by governments will incentivize the farmers to adopt regenerative practices through subsidies, tax breaks, or other similar mechanisms [3, 14, 15, 18].

13 Conclusion

Soil regeneration is a crucial process for maintaining and improving the health of our soils. It involves various practices and techniques aimed at restoring soil fertility, enhancing its structure, and promoting the growth of beneficial microorganisms. Through the adoption of sustainable agricultural practices, such as cover cropping, crop rotation, and organic amendments, farmers can contribute to the regeneration of degraded soils. Additionally, the integration of modern technologies like precision agriculture and remote sensing can aid in monitoring soil health and guiding management decisions. However, further research is needed to better understand the complex interactions between soil components and processes, as well as to develop innovative strategies for soil regeneration.

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Impact of Regenerative Agriculture on Soil Erosion

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Abstract In current civilization, soil erosion can be considered one of the main issues faced in the agricultural system. Conventional agricultural practices have severely jeopardized regular agricultural activities, affecting yield production, and degradation of environmental stability has been a significant factor in deteriorating soil quality and health over the years. In order to improve soil quality and biodiversity, the world is seeking an alternative option. This is when regenerative agriculture emerged as a promising approach with better land management strategies and means of sustainable agriculture. This chapter highlights the factors affecting soil erosion and their impact on biodiversity, and how regenerative agriculture helps in controlling and preventing soil erosion to increase agriculture productivity and ecosystem health. It also examines the mechanism and effects of various regenerative agricultural framing practices such as Crover cropping, no tilling, Agroforestry, crop rotation, intentional grazing, and mulching, etc. on reducing soil erosion rates, enhancing soil structure, and protecting against extreme weather conditions. This chapter also discusses the benefits and contributions of regenerative agriculture beyond soil erosion such as increased soil organic matter, improved water infiltration, and enhanced nutrient cycles, etc. these factors not only help prevent soil erosion rates but also promote soil fertility and long-term sustainability. It also reviews the case studies, experimental studies, and real-life examples to underscore the effectiveness of these practices in reducing the vulnerability to soil erosion and enhancing the quality of soil thus improving agricultural productivity for farmers. By comprehending its advantages, this chapter proposes the widespread adaptation of regenerative agricultural practices for building more resilient and sustainable agricultural systems to improve soil quality across the globe for coming generations.

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1 Introduction to Regenerative Agriculture

More than 38% of the total land of the earth is occupied by people for agricultural purpose. It becomes sole responsible of every individual to inculcate the methods of Cultivation that are optimising, simplified and are environmentally stable. Regenerative farming is a method of producing food that is nutritious and has a sustainable impact on the soil and Nature. It can be considered as one of the most effective ways of meeting the nutritional requirements for the enormously growing human population without causing any damage to nature. It addresses the benefit of soil health improvement, renewing the overall mineral content, and water retention. It minimizes the usage of chemical fertilizers in the soil and it promotes the usage of microorganisms for improving soil health. Sustainable Agriculture requires various agricultural methods that are embedded with microbiota and Complex living systems which will help in reducing the plateauing of the yield. Sustainable agriculture results in the production of Significantly high yields of food that is extremely nutritive. Sustainable agricultural practices employ cultivational techniques that will cut down on the use of synthetic chemicals and further aid in the activation of the nutrient flow systems. Better crop nutrition is ensured by nutrient-flow systems which are more effective and less damaging to the environment. These systems generate a new upward flow of nutrients in the soil profile. By definition, Such a procedure constitutes soil genesis.

1.1 Regenerative Agriculture and Its Overview

The most current agricultural innovation, known as "regenerative agriculture," aims to stop soil erosion and restore soil content. Regenerative agriculture benefits the microbiota, plants, productivity of the soil, and water in a symbiotic way. It also has the potential to be effective in slowing or stopping climate change. Regenerative organic farming is what it is known as, and it uses organic methods. By boosting the soil's biodiversity and microbiota at the same time, regenerative agriculture principally strives to raise the mineral and nutrient levels of the soil. Its primary agricultural strategy focuses on soil preservation and environmental support. Regenerative farming techniques include reducing the use of external items, rotating crops, using manure, improving soil, and using microorganisms to repair the environment.

1.2 Major Concern in the Agricultural Sector- Soil Erosion

Soil Erosion is a major environmental issue and is a long-term effect which disturbs Agriculture, Soil Potentiality and fertility. Soil Erosion leads to loss of organic matter, nutrients, living creatures, and total soil depth by increasing the water loss thereby reducing the productivity of the land. This procedure not only removes the soil's top layer of humus but also depletes it of vital minerals, which has an impact on plant growth.

There are numerous significant effects of soil erosion that might affect the environment. Loss of soil depth causes a decline in the productivity of the land, which has an impact on agriculture. Agricultural soil erosion, which led to the loss of vegetation in the soil, is mostly linked to human-induced soil erosion. The removal of topsoil has a negative impact on soil structure and water penetration. Eradication of the topsoil causes low fertility levels, which lower agricultural yield. By reducing soil erosion, regenerative agriculture helps keep nutrients on the surface and prevents nutrient runoff.

2 Soil Erosion: Factors and Impacts

2.1 Types of Soil Erosion

Soil erosion is a process whereby the upper layer of soil wears away. This is contributing to deterioration in the soil. This natural process is made up of dynamic reactions caused by erosive agents such as water, ice, snow, air, plants and animals. Several types of erosion, depending on these agents, may occur, such as water erosion, glacier erosion, snow erosion, wind erosion, zoogenic erosion, and human erosion, such as tillage erosion. Types of soil erosion include.

2.1.1 Water Erosion

Water erosion is the loss of the top layer of land due to irrigation, rainfall, snowmelt, runoff, and poor irrigation management. Once it comes to this issue, it's believed that precipitation is usually to blame. Flowing water moves organic and inorganic particles of soil down the ground surface and deposits them in the lower landscape. Floods would result in the long run [17]. Water erosion occurs as the result of the detachment and transport of soil by rainfall, runoff, melting snow or ice, and irrigation. Erosion may also impact water conveyance and storage structures, and contribute to land surface pollution. For use within stream channels, forest areas, and construction sites, specialized erosion control practices have been developed [29].

2.1.2 Wind Erosion

Wind erosion is the process of nature through which the wind transports and deposits dirt. It is a common occurrence in dry, sandy soils or soils that are loose, dry, and coarsely granulated. Wind erosion causes damage to natural plants and soil by transferring dirt from one spot to another. Wind erosion is produced by the movement of sand and dirt generated by the wind [58]. Soil erosion by wind is a process of eroding, transporting and depositing fine particles and nutrients from the surface soil under the action of wind force. Wind erosion increases sand and dust pollution, has a certain effect on soil carbon dioxide (CO_2) emissions, and accelerates the melting of the snow mantle and the rise of the snowline [94].

2.2 Factors Affecting the Soil Erosion

Soil erosion is influenced by various factors, with precipitation intensity being a primary driver as heavy rains can dislodge and transport soil particles. Vegetation plays a crucial role in erosion control, as dense plant cover can stabilize soil through root systems and canopy interception. Additionally, land slope and human activities like deforestation and improper land use can exacerbate soil erosion, posing significant environmental challenges.

2.2.1 Rainfall Amount and Wind Velocity

Rainfall is the most potent component of erosion, causing splash and runoff. Raindrop erosion is the splash generated by water droplets coming into direct contact with soil. Although raindrops do not slap soil in shallow streams, they do create turbulence, which boosts sediment-carrying capacity.

2.2.2 Land Slopes

Slope accelerates erosion by boosting the velocity of flowing water. Small variations in slope cause severe damage. According to hydraulic laws, a four-fold increase in slope equals twice the speed of flowing water. This increased velocity can quadruple erosive power and triple carrying capacity. In one experiment conducted in the United States of America, it was determined that the total loss of soil per hectare due to erosion in a maize plot was 12 tonnes when the slope was 5%, but it could reach 44.5 tonnes when the slope was 9%.

2.2.3 Soil Physical and Chemical Properties

Several soils erode more easily than others under the same conditions. The soil's appearance, framework, and organic matter, as well as the quantity and type of salts around, all have an impact on its trustworthiness. Sandal soil absorbs water quickly due to its high permeability, resulting in reduced erosion. Increased organic manure content in the soil improves granular structure and water retention capacity. As organic matter degrades, so does soil trustworthiness. The soils of credibility are fine-textured and alkaline.

2.2.4 Kind and Breadth of Ground Cover

Plants on the surface help to decrease erosion. Forests and grasslands cover more ground than planted crops. Vegetation decreases the amount and rate of surface runoff, allows more water to infiltrate into the soil, and enhances soil storage capacity by intercepting the erosive pounding action of falling raindrops. The absence of vegetation creates an environment that is prone to erosion [27, 95].

2.3 Effects of Climate Change on Soil Erosion

Climate change describes permanent alterations in the Earth's climate, most notably the rise in global temperatures, which is generally attributable to human activity, most notably the use of fossil fuels (coal, oil, and natural gas) and deforestation. These activities are known to release greenhouse gases (GHGs) into the atmosphere, such as CO 92 (CO 62), Methane 92 (CH 84), Nitrous oxide (N_2O 92), and fluorinated gases (F 2). These gases trap solar heat, keeping it from escaping into space, and cause the Earth's surface temperature rises, resulting in variety environmental consequences. Climate change may have a substantial impact on soil erosion processes, aggravating current problems and introducing new ones (Fig. 1) [35].

2.3.1 Increased Intensity and Frequency of Rainfall

Climate change has the potential to modify precipitation patterns, resulting in more severe and frequent rainfall events in some areas. Heavy rainfall can cause water to flow off fast, increasing surface erosion rates. Raindrops striking the soil surface can also break down soil aggregates, making it more prone to erosion [64].

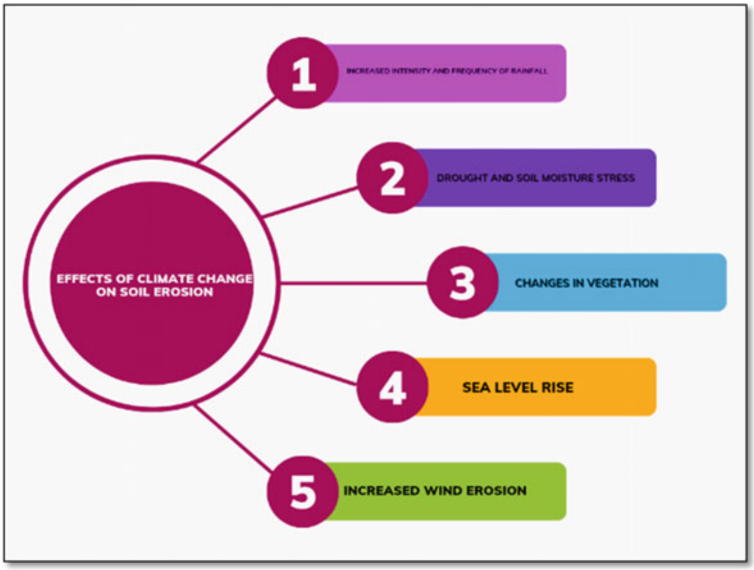

Fig. 1 Effects of climate change on soil erosion

2.3.2 Droughts and Soil Moisture Stress

Climate change has the capacity to cause extended droughts and periods of low rainfall in some locations. Soil moisture stress decreases plant cover, making the soil more susceptible to wind and water erosion when precipitation occurs. Droughts can also impair soil stability, making it more susceptible to erosion during following rainfall events. It can also reduce soil enzyme activity, resulting in slower nutrient turnover [10, 76].

2.3.3 Changes in Vegetation

Higher temperatures and changed precipitation patterns can have an influence on the distribution and development of plants. Changes in vegetation cover can have an impact on the protection given by plant roots and leaf litter, both of which play an important role in erosion reduction. Reduced vegetation may expose soil surfaces to erosive pressures [96].

2.3.4 Sea Level Rise

Sea level rise induced by climate change could lead to saltwater intrusion in coastal regions. Soil salinization reduces soil stability and makes it more prone to erosion.

Coastal erosion can also be exacerbated by higher storm surges and wave activity, both of which are connected to climate change [54].

2.3.5 Glacier Retreat and Permafrost Thaw

Climate change drives glaciers to recede and permafrost to thaw in colder locations. These modifications have the potential to enhance sediment transport to rivers and streams, resulting in increased rates of erosion downstream. Thawing permafrost can also result in the formation of new erosion features such as thermograms depressions and gullies [6].

2.3.6 Increased Wind Erosion

Climate change can modify wind patterns, making wind events more common and powerful in some areas. Wind erosion can deplete soil fertility and erode topsoil, providing problems to agricultural output [30].

2.3.7 Erosion-Induced Carbon Loss

During soil erosion, soil organic carbon loss can result in reduced soil fertility and carbon sequestration capability. This increases the emission of greenhouse gases, increasing climate change [5, 9].

2.3.8 Land Use Changes

As farmers and communities adapt to changing conditions, the effects of climate change may influence land use patterns. The increased soil erosion rates can be attributed to changes in land use such as deforestation or urbanization, due to lower plant cover and changes in land management methods [34].

2.4 Effects of Soil Erosion on Environment and It's Surroundings

The phrase "environment" implies the conditions or surroundings in which living creatures, including people, live. It includes both the natural and artificial constituents of the Earth's systems, and it serves as the framework for all ecological activities. The environment is comprised of social, cultural, and economic variables that impact the quality of existence and the relationships between living beings and their surroundings. Soil erosion may have major and far-reaching environmental implications, influencing numerous natural systems and resulting in ecological, economic, and societal ramifications. Some of the key environmental effects of soil erosion are described in the following: [44, 71].

2.4.1 Loss of Fertile Topsoil

Topsoil that has been eroded contains essential minerals and organic materials for plant development. Fertile topsoil is lost as a result of soil erosion, resulting in poorer agricultural production and crop yields [39].

Water Quality Degradation: It can carry eroded soil particles into bodies of water such as rivers, lakes, and streams. This sediment-laden runoff can harm water quality by increasing turbidity, decreasing light penetration, and introducing contaminants such as pesticides and fertilizers clinging to soil particles. Water pollution may affect aquatic ecosystems and animals by changing their habitats and compromising their health [36].

2.4.2 Increased Flooding

Soil erosion has potential to disrupt hydrological cycle, resulting changes in water flow patterns. Large volumes of dirt swept away can block streams and drainage systems, increasing floods during severe rain storms. Floods can be exacerbated by the loss of the soil's structure and reduced capacity for infiltration [53].

2.4.3 Landslides and Instability

The structural integrity of slopes and hillsides is weakened by soil erosion. This greater instability can result in landslides, particularly during periods of high rainfall or when vegetative cover is eliminated. Human communities, infrastructure, and natural ecosystems are all threatened by landslides [42].

2.4.4 Reduced Carbon Sequestration

Soil erosion causes the loss of naturally occurring carbon, which is essential for soil wellness and fertility. The carbon contained in eroded soil is released into the atmosphere as carbon dioxide (CO_2) as it is taken away. This causes increased atmospheric emissions of greenhouse gases, leading to climate change [61].

2.4.5 Desertification and Degradation

Soil erosion can lead to desertification, a process in which once-productive land becomes barren and unable to sustain vegetation. As rich topsoil is depleted, the land degrades, making it difficult for plants to develop roots and flourish, prolonging the degradation cycle [34].

2.4.6 Habitat Loss and Biodiversity Decline

Soil erosion may destroy natural ecosystems, shifting plant and animal populations. Alteration in cover of vegetation and soil quality caused by erosion can lower biodiversity and disturb ecological balance, affecting a variety of plant and animal populations [50, 63].

2.4.7 Economic Losses

Soil erosion has both environmental and economic consequences. Farmers, towns, and governments may suffer financial losses as a result of reduced agricultural production, impaired water supplies, increased floods, and infrastructure damage [16].

3 Practices for Controlling Soil Erosion

Soil Erosion takes place naturally all the time. The erosion potentiality of any surface is determined by basic factors such as characteristics of the soil, topography, vegetation, and climate of the area.

3.1 Key Practices for Controlling Soil Erosion

If the erosion problem in agriculture is not severe, it can be addressed through crops or vegetation and agronomic measures [7]. Conventional methods such as bund construction and river dam construction are considered the most effective way to stop soil erosion on a large scale. Construction of canals in agricultural regions can also aid in soil erosion since water has to discharge somewhere; if there is not anywhere for it to runoff, it will flow through crops, causing soil erosion. Windbreaks and shelter beds can also be considered effective means for preventing soil erosion caused by the wind. Bunds and Dams can also stop soil erosion. Sustainable and regenerative agricultural methods such as Terracing, windbreaks, shelter beds, no-tillage agriculture, Contour agriculture, Adaptive Multi-Paddock (AMP) grazing,

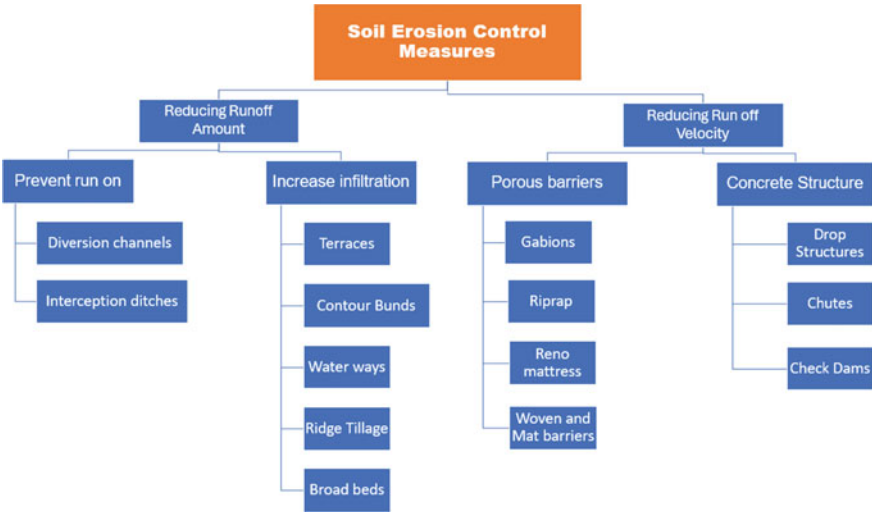

Fig. 2 Figure showing various methods to control soil erosion

organic mulching, Perennial cropping systems, Cover cropping, Crop rotation also stop soil erosion. There are other types of erosion control measures based on two factors one is the amount of runoff and the velocity of runoff. For controlling the amount of runoff, diversion channels, and interception ditches are used to prevent run-off, terraces, counter bounds, etc., are used to increase infiltration. For controlling runoff velocity techniques like gabions, riprap, woven & mat barriers, etc. are used as porous barriers, and methods like check dams, chutes, etc. are used as concrete structures. A clear representation is given below (Fig. 2).

3.2 How Regenerative Agriculture Address Soil Erosion

In recent years regenerative agriculture has been recognized for its conservational methods and sustainable land management practices. The main principle of regenerative agriculture is to preserve soil structure, enhance soil fertility, and promote natural resources that protect from soil erosion. In order to successfully combat soil erosion, regenerative agriculture integrates basic fundamental ideas and major important practices to improve the overall structure of the soil, prevent loss of sedimentation, improve water retention capacity, etc. As Terracing, windbreaks and shelter beds, no tillage agriculture, Contour agriculture, Adaptive Multi-Paddock (AMP) grazing, organic mulching, Perennial cropping systems, Cover cropping, Crop rotation, have proved effective when adopted in various cases/regions based on the requirement.

Practicing and adopting these techniques/practices may be able to minimize soil disturbance, increase organic matter content, and thus may benefit farmers. Terracing is an ancient anthropogenic process followed in hilly slopes or mountainous regions since thousands of years, as a system to mitigate floods, reduce soil erosion. Terracing can be defined as the anthropogenic process which involves creating spaces in slopes to practice agriculture or terracing can be defined as the process of practicing agriculture by constructing terraces in slopy areas. poor designing and construction of terraces can increase soil erosion so proper care must be taken in construction of terraces. This method stops soil erosion by reducing speed of runoff of water flowing through terraces, they also add biomass to soil through accumulation of biomass in terraces [93].

Windbreaks also known as shelterbelt/shelter-bed is an agroforestry technique employed by laying two to three layers of trees and shrubs around the agricultural fields. Mainly fruits and comically beneficial plants. this method the heavy winds are stopped by plants and prevent loss of soil. The almost care of plants planted for windbreaking [85].

Mulching in this agricultural technique the soil in fields is covered using hay or polythene covers. Mulching prevents all types of soil erosion. Mulch prevents growth of weeds which are major biological problem to soil erosion. This method stops soil erosion by preventing sediment to runoff [88].

Grazing techniques like rotational grazing and Adaptive multiped lock are effective against continuous grazing methods in which the cattle are made to graze in a specific location under farmers supervision and then they are moved to another location for grazing in between the old pasture is allowed to grow. These methods can be extremely effective against soil erosion since this method allows grass to grow again unlike continuous agriculture in which the complete plants are grazed but in this method some grass are left to regrow [3].

No tillage Agriculture This method of agriculture farmers does not till the agricultural land they grow corps directly without any tillage. No tillage must be done with a mix of various methods like crop rotation, mulching etc. This method prevent soil erosion since no tillage is done thus top soil is prevented from exposing to external atmosphere thus stops topsoil escaping thus preventing soil erosion [20]. Perennial crops this type of cropping involves growing of crops which gives yield throughout year. Perennial crops occupy 30% of total cropping in the world. Perennial cropping helps to halt and prevent soil erosion since the crop plants are present throughout the year this plant supports soil from runoff thus preventing soil erosion [47]. Cover cropping are the crops that are cultivated to cover soil. They have a very short life span. This crop stops growth of weeds, and increases surface residue that decreases soil erosion. Cover cropping is generally done in between of two crops [48].

4 Regenerative Agriculture: A Solution to the Problems of Soil Erosion and Its Impact on Soils Health in the Present Era

When using Conventional agricultural practices, removing vegetation that protects soil, and tilling the topsoil through mechanical processing are 2 major ways where erosion rates were affected [79]. Most civilization doesn't realize that soil loss and erosion are the two most serious issues it faces [40] in the current era. Though it is caused based on various reasons. The world still needs a way/solution to address these issues by aiding farmers with fewer input costs while also increasing the net income at the same time. Here is where regenerative agriculture comes into the picture, this farming practice not only reduces soil loss and limits chemical usage but also builds up the soil structure [40], and also improves soil health, thus increasing the yield. They also help in preserving local ecosystems and maintaining balance in the environment [62].

4.1 Regenerative Agricultural Practices: A Regenerative Approach to Increasing Soil Quality

Many farmers, researchers, and organizations often believe that using regenerative agricultural practices helps improve soil quality and quantity in the agricultural sector. Some of them are trying to design principles for co-existing with nature harmoniously, while others are trying to make better use of the limited resources. When using conservational agricultural practices, they observed that these practices are gradually reducing the amount of CO_2 and N_2O levels in the soil and reducing the amount of nitrogen dioxide in the bay area [15]. To restore these levels in the Bay area and soil in the farmlands near the Bay area, they have designed basic principles for the successful practice of regenerative agriculture. They are:

1. Minimize the soil's biological, chemical, and, physical distribution [82].
2. With natural materials and vegetation, keep the soil covered.
3. Increase the plant diversity in the area.
4. The root system should be kept as low as possible in the soil.
5. Incorporate rotational grazing and animal practices as much as possible into the farms.

And for the areas near the tropical regions with more rainfall, there were five sample principles for sustainable and regenerative growth of crops. They are as follows:

1. Keep the soil covered.
2. Eliminate or minimize all soil tillage.
3. Increase biomass production.

4. Increase the biodiversity and strongest of all
5. Feed the crops with mulch.

Though there are similarities in the above both sets of guidelines, those were designed according to the geological location and nature of the soil, based on their years of experience. Both these sets of guidelines helped in improving both the quality and health of the soil.

When we are talking about Regenerative agriculture farming practices, we often talk that they vary based on the type of soil they are being practiced. Here is a list of a few Regenerative Agricultural farming practices which are commonly used in controlling soil erosion.

4.1.1 Crop Covers

Cover crops, as the name indicates, are nonprofitable crops usually grown before or after cash/main crops. These crops can also be grown along or outside the corps, as they help in recycling nutrients back and forth into the soil, they act as scavengers and suppress weeds by competing for resources when planted along. When planted after harvest they break down the excess nutrients present.

These crops also help in breaking down soil particles through roots and act as natural tillage without disturbing the overall structure. Having these crops year alone helps in improving soil health, building up organic matter in the soil, and increasing water retaining capacity in addition to controlling the rate of soil erosion [48]. They also help in slowing evaporation and cooling soil. Several multispecies cover crops can be employed based on land requirement and the type of main crops being plants such as legume cash crops helps in fixing nitrogen from the atmosphere and contribute to the required crops [48, 77], grass species like rye (Secale creale L.) have stabilizing root system and also provides a large quantity of surface residue [81].

4.1.2 No-Till Framing

No-till farming, in other words, the complete elimination of tillage in the agricultural system [25]. During the planting of crops, we often till the land in order to sow seeds. When we till the land too much it leads to the disruption of soil present underneath. Each disruption disturbs the microbial community & also loosens the topsoil which leads to the instability of plants above the soil [52].

In No-till or Conservational till framing method, seedlings are directly sown into topsoil with minimum disturbance to the soil layer. At the time of harvest, the plant residues are left in such a way that they cover the soil surface completely. These plant residues act as a barrier and intercept the raindrops on impact and also prevent pore clogging and also retain surface runoff [79]. This practice helps increase water penetration and retention capacity, improves soil nutrient retention, and increases soil organic matter over time, thus rebuilding the soil surface for future generations [31].

4.1.3 Crop Rotation

During Conventional Agricultural practice, we often see that the same crop is grown continuously on the same piece of farmland. This will gradually deplete the natural nutrients [15], degrade the topsoil, decrease the water holding capacity, and reduce the water retention capacity on the farmland.

Multispecies agro-system has proven effective in this situation [37]. This system consists rotation of crops, where crops are rotated based on types of roots especially in between deep roots and shallow roots to help in fixing certain nutrients in the soil [15]. It is the potential component for soil conservation & bio-diversity strategies [37]. Based on the type and requirement of farmland influence of intense rotation of crops improves the overall soil structure, increases water filtration capacity in the soil, and also controls soil erosion [21].

4.1.4 Agroforestry

Agroforestry is the combination of trees and shrubs with agricultural practices. They not only help in preventing soil erosion but also in increasing soil fertility, enhancing water retention, and reducing water run-off.

Trees are natural windbreakers, as the leaves of the trees reduce the power of wind and rain. Planting crops between already existing trees not only increases plant diversity but also protects the soil by preventing topsoil erosion [31]. The roots of these trees and shrubs play a crucial role in maintaining soil structure [97]. For a field to be called agroforestry, it must satisfy the 4 I's, which are Intentional, Intensive, Integrated, and Interactive [91].

In the United States Agroforestry is categorized into 5 types. They are as follows:

(a) Alley Cropping: It is also called intercropping. In this type, crops are grown between trees.
(b) Forest Farming: It is also called multi-story cropping, as herbs, botanical or decorative crops are grown between the crops.
(c) Silvo Pasture: It is the combination of Livestock and forage with trees on one piece of land. Trees provide shelter for life stock and forage during different climatic conditions and also provide food, timber, etc. [31, 91].
(d) Riparian Fast Buffers: There are areas present near the shorelines of streams and rivers. the tree roots stabilize areas near the shorelines of streams and rivers and prevent soil erosion [83].
(e) Wind Breakers: They shelter agriculture fields from wind, rain, etc. They also support wildlife [91].

4.1.5 Integration of Livestock and Rotational Grazing

The isolation of animals from farms has raised pollution, exposed animal health to dangers, and resulted in inappropriate manure disposal [31]. Allowing livestock on farms helps in many ways, such as regenerating and repairing soil after the natural nutrient cycle [52], improving the rate of water into the soil, and reducing soil erosion [86] after a certain grazing period. After the crop harvest, as the animals move around the farm, they leave manure behind to improve fertility and nutrients in the soil [52]. They also assist in obtaining organic carbon manure by converting high-carbon residue [31].

Crop Livestock system [19] can be treated as an alternative to conventional Agricultural systems not only for increasing productivity but also as an opportunity for land diversity [86]. It also has advantages for farmers in multiple aspects, such as environmental diversity, and economic and social benefits [89]. This system can have negative or positive effects based on grazing arrangements [19].

Other than the above-mentioned practices, there are few regenerative agricultural practices that are based on the geological, and topographical locations of the soil. A few of them are listed below.

(a) ***Composting***: In this practice, the farms are treated with organic compost which was formed by turning wastes like manure and food into fertilizer by natural process [57].
(b) ***Nutrient management***: Helps farmers estimate and understand how much nutrients are required for crops to prevent excess from leaking into local water bodies [15].
(c) ***Water Management and Diversion***: By building water diversion, they help in managing water bodies effectively across the land. During heavy downpours of rain, they prevent soil erosion by distributing water across the land [52].
(d) ***Stream Side Fencing***: By constructing fences along the streamline reduces the pollution caused by the farms. Fencing keeps the livestock and their wastes away from the water bodies reducing pollution and erosion problems [15].
(e) ***Mulch with Plants***: Mulch locks moisture in the soil and also regenerates topsoil by adding extra nutrients by breaking down the top layer [52], etc.

4.2 Impact of Regenerative Agriculture Framing Practice on Soils Health

Soil Erosion is not always caused by hostile climatic changes, downpours, etc. It can also be caused by the results of land mismanagement and practicing appropriate farming methods in various farmlands [11, 92]. Though Sustainable/Regenerative Agriculture helps in controlling the rate of erosions, in the end, it depends on the nature and health of the soil in that specific farmland. In the agricultural system, the nature and health of soil play an essential role in determining and understanding the types of practices and crops planted on the farm. When these farming practices are applied to farmlands, they vary based on the geological location, topography, soil nature, soil health, etc., The results that we expect can be seen only by applying the correct methods/practices based on the situation of farmland. Despite the facts, some studies have demonstrated that applying appropriate practices to appropriate situations has proven effective by increasing soil fertility, enhancing water retention, improving soil health, controlling soil erosion rates, and thus enhancing the yield of the crops to farmers (Table 1).

5 Effects and Benefits of Regenerative Agriculture on Soil Erosion

5.1 Role of Microorganisms in Regenerative Agriculture

The agricultural sector is highly sensitive to climatic changes at the intensive use of agricultural practices contributes to the significant increase in global warming. To meet the food requirements of the growing population, conventional/modern agricultural practices are heavily dependent on chemical inputs. More usage of these chemicals/techniques not only harms the environment and human health [84] but also gradually leads to the depletion of the quality and productivity of the soil [51]. When the quality of the soil is disturbed, it disturbs the harmony of microbial colonies present within it, thus affecting the soil biodiversity. Soil biodiversity is an essential component of soil development and preservation [90], soil microorganisms are responsible for the maintenance of function in both natural and managed soil [4]. They also play an essential role in maintaining while acting as plant growth promoters, biological controlling agents, bio remediators, nitrogen fixers, etc. [51].

The key features of Regenerative Agriculture are the restoration of soil health, carbon sequestration, and protection of soil biodiversity. It can be interpreted as; the welfare of microorganisms is determining factor for the success of regenerative agricultural practices [32]. Soil Microorganisms are also called plant growth promoters as they contain beneficial traits such as the synthesis of Phyto hormones [51]. They do not cause any harm to soil at any level instead they play an important part in preventing soil erosion and they can be an important factor that can promote regeneration of soil. Considering biological activities and their functions microbes like Rhizobium, mycorrhiza azotobacter can be used in providing nutrients to the soil thus improving soil health.

Rhizobium is a genus of bacteria they are gram-negative in nature they belong to the family *Rhizobiaceae*. They form a symbiotic association with leguminous plants and then form root nodules. Rhizobium acts as a nitrogen fixator, rhizobium in root nodules converts nitrogen to ammonia which can be absorbed by plants. Some rhizobium species like *Rhizobium tropici* produce an Extracellular Polymeric Substance (EPS) this polymer mixed in soil improves soil strength of load bearing consequently preventing soil erosion [46].

Mycorrhiza is a Phyto-fugal symbiotic relation in which the roots of plants join with the hype of fungi this fungus creates a huge network in the soil to provide nutrients for plants by absorbing nutrients from the soil. Mycorrhiza also provides defense to plants [41]. So, mycorrhiza can be used in regenerative agriculture as a

Table 1 List of case studies/experimental studies/real-life examples of various regenerative agricultural farming practices used in different areas/regions to address different issues/objectives

Area/Region	Objectives/Issues	Types of practices used	Results	References
Tropical Rain Forest	i. Unable to grow food crops during rains ii. Nutrients are getting washed away due to rain	Cover cropping and No-till farming (Maize/Mucuna system)	Soil fertility improved over the years, protecting from losing nutrients and topsoil from rainfall	[13]
Upper Tana River Basin, Kenya	i. Due to the increase in the temperature (2 °C) there was a reduction of species richness near the basin	Agroforestry, Green water management (GWM), Mulching	GWM and Mulching helped in the decrease of sedimentation and prevented soil erosion from banks Agroforestry helped in agricultural development, protecting Bio diversity, increasing natural fauna	[28, 38, 55]
The Zemaicia uplands in Western Luthiyana	i. Identification of crops and agricultural rotations that will reduce soil erosion	Crop rotation	When compared to field crop rotation, on arable slopes of 2o-5o, 50–100, and 100–140, grass-grain rotation (>50%) reduced soil loss by 77–81%, while grass-grain rotation (50%) reduced soil loss by 21–24%	[37]
Eric Niemeyer's MadMax Farms in Ohio	i. Soil Consists of slits and clay loams ii. Due to erosion, the soil gets washed away in concentrated areas and gullies are formed	Multi-species cover cropping and No-till farming	He has been seeing a consistent increase in the yield over the years His yield increased from a. 165 to 195 bushels per acre for corn b. 45 to 65 bushels per acre for soybean	[49]
Beltsiville Agricultural Research centre, Sustainable Agricultral Demonstration sites in Beltsville, Mary land	i. To evaluate economic risks & profitability of sustainable vegetable & grain production ii. To assess the long-term impact of cover crops in crop rotation	Cover crops, No-till Framing	In this experimental investigation, the results demonstrated that a crop cover-based approach maintains a good gross margin while decreasing pesticide dangers by about one-tenth of recommended tillage	[48]

(continued)

Table 1 (continued)

Area/Region	Objectives/Issues	Types of practices used	Results	References
Patzcuaro watershed Mexico	i. To assess the influence of Mazie cropping with conventional tillage and no tillage on soil quality	No-tillage	The results indicated that the use of No tillage method significantly increased soil quality and further restored soil structure, microbial activity, and soil enzyme activities	[73]
Oxiol site in Brazilian cerrado site	i. To explore the impact of various land uses and soil management strategies for controlling rate of erosions, and improving water capacity in soil	Livestock grazing or Rotational grazing, No-till farming	The experimental investigation found that proper agriculture management, integrated agricultural systems, especially rotating crop-livestock systems, enhanced soil infiltration and reduced soil erosion	[86]
Southern Otanario organic farmers No till experiment	i. The role of cover crops in organic till method ii. No-till agronomic and vegetable cropping practice	Organic No tillage & Cover crops	• Cover crops have been shown to be effective in organic no-till methods for both agronomic and vegetable crops • The ability of cover crops to suppress weeds is critical in agronomic crops • The effect of cover crop mulch on vegetable crops is variable	[8]
Southern Wisconsin	i. To explore the soil bacterial populations associated with continuously vs. yearly rotating maize (Zea Mazie L.) and soybean (Glycine max L.) ii. Determine the influence of frequently employed grass cover crops on soil microbial communities after one season	Crop rotation & Cover crops	• Bacterial populations were unique in continuously planted corn and soybean • During the rotational cycle of these crops, the cultures are identical • The effect of grass cover crops on soil bacterial communities was not significant	[21]

fertilizer and manure too. Azotobacter is a genus of bacteria that produce a wide range of biological chemicals that enhances soil by providing nutrition and yield stability to crop. Cyanobacteria is also known as blue-green algae is a gram-negative bacterium, they are photosynthetic organisms. Cyanobacteria can avoid soil erosion and help conserve water [75]. An experimental comparative study conducted in India to compare the efficacy of microorganisms between conventional and regenerative agricultural practices revealed that regenerative agricultural practices were effective in enriching the soil bacterial community while also improving soil health [84].

5.2 After Effects of Regenerative Agriculture on Soil Erosion

5.2.1 Restoring Soil Health and Fertility

Regenerative agriculture has some of the best practices that increase soil fertility of a region but the practices are effective only to a small scale and ineffective at a large scale, no till can reduce soil erosion but it requires a lot of herbicides since no till allows water to infiltrate into soil. but RA practices are very effective for a small scale of land to increase soil quality [78]. Usage of biofertilizers like *Rhizobium tropic* can be used to strengthen soil therefore increasing soil quality [75].

Terracing has been shown to reduce runoff and soil loss by reducing the impact of water erosion on soils [74], Adaptive Multi-Paddock (AMP) grazing has found to have 13% more soil carbon and 9% more soil nitrogen when compared to common grazing sites in south eastern grazing lands of U. S. [56].

In Gran Chaco region of Argentina, the demand of beef and soy around the globe has led to deforestation as the reason soil erosion, flooding and salinity as the result Argentina implemented native forest law. The latter has then banned deforestation and implemented Agrosilvopastoral techniques which include a combination of cattle grazing, growing trees and producing economically important commodities [12].

It is found that organic mulching applications has a grater effectiveness its application has refused runoff up to 6–10 Mg ha-1. Straw was found to be a best material for organic mulching. Plantation agriculture in tropical regions increases soil erosion. When compared to any conventional methods [18]. Windbreaks are found to be very satisfactory among the U.S 77–99% of farmers in U.S prefer wind breaking technique. In this way, direct and indirect benefits to farmers, soil erosion due to wind was effectively curtained [85].

In cerrado region of Brazil soil lacks phosphorus in it. It required a lot of inorganics to make soil rich in phosphorus. Later a study was conducted using continuous tillage and No tillage was used in different fields of Cerrado region it was found that No tillage increased 70–88% prosperous in the soil [72].

5.3 Reduction of Soil Erosion Rates and Loss in Sediment

Regenerative agricultural practices such as mulching terracing, cover cropping, and no-till farming are superior methods compared with conventional methods they enhance soil health and prevent soil erosion without decreasing crop yield. The regenerative agricultural methods like cover cropping and no-till agriculture and prevent soil loss of nutrients from runoff due to rains and other reasons. Soil management practices such as terracing and regenerative soil health management practices like using organic compounds such as vermicompost in soil and introduction of biofertilizers helps in increasing soil health.

5.4 Ecological Benefits of Regenerative Agriculture on Soil Erosion

So far, we have discussed the various types of regenerative agricultural practices and their impact on preventing soil erosion. When it comes to benefits, these practices have shown significant ecological benefits in controlling soil erosion. Various strategies have been implemented to reduce erosion risks, as soil health is highly prioritized in these practices. An increase in the production of biomass has improved the fertility of soil, thereby preventing soil degradation.

With the adoption of these techniques, farmers have witnessed improvements in soil health and fertility, as evidenced by healthier crops and improved yields. Moreover, they observed higher soil moisture content and sponginess in comparison to previous practices. Soil tests, and visual signs, such as the presence of earthworms, revealed the abundance of microbial communities in the soil. These techniques contributed to the reduction of the use of chemical pesticides, thus preventing the formation of algal blooms. They also facilitated the recharge of groundwater and improved the quality and quantity of water resources across the farmlands.

Farmers and farm owners were able to see an increase in their net income by reducing the costs of using heavy machinery, and the use of chemicals, herbicides, pesticides, and fertilizers. Besides this, they were able to earn diversified revenue streams by adopting a mixture of suitable techniques based on the nature of their farms. Through reduced usage and exposure to harmful chemicals, farmers and farm workers have seen a significant improvement in their health. These techniques provide local employment and healthier food choices, aiding in the growth of rural economic development.

6 Government Policies to Reduce Soil Erosion Through Regenerative Agriculture

There are various government policies that are being implemented by governments across the globe to prevent soil erosion many of them encourages farmers to implement regenerative agriculture practices through sustainable agriculture.

Many countries like New Zealand are planning to Implement regenerative agriculture at large scale through The Regenerative Agriculture Initiative. There are many policies across the globe that are implemented by governments at various levels in the table given below we can see some of the initiatives implemented in various countries across the globe (Table 2).

Due to these policies, many farmers are being educated and many are applying regenerative agricultural techniques, according to the reports of the Ministry of Agriculture and Forestry (BHA), at least 11 lakh hectors of land are being cultivated by using these techniques in India under PKVY policy in 2022. Similarly, many countries are adopting regenerative techniques to avoid soil erosion. However, the aims are too ambitious but the progress or achievements of these policies are very minimal. Governments must work more on regenerative agriculture the government agencies with utilizing Morden technologies as much as possible. In the end, the use of NGOs under public private partnership to educate farmers on the benefits of regenerative agriculture can be a great advantage in improving the results.

Table 2 Initiatives implemented in various countries across the globe

S.no	Country	Initiative	Aim
1	USA	Soil health initiative	Prevent soil erosion and improve overall soil health
2	India	Paramparagat Krishi Vikas Yojana (PKVY)	Prevent soil erosion, enhance soil fertility, and promote sustainable agriculture
3	Australia	National soil strategy	Improve soil structure and reduce erosion risks
4	China	Soil ten plan	Restore soil health and combat erosion
5	France	Plan écophyto	To minimize the use of chemical pesticides and fertilizers in agriculture and promote more sustainable farming practices
6	Ethiopia	Agricultural Growth Program (AGP)	Enhance soil fertility, prevent erosion, and boost agricultural productivity in the country
7	Germany	BÖLN	Prevent soil erosion and improve the overall ecological sustainability of farming
8	Kenya	Climate-smart agriculture program	Promoting agricultural practices that are resilient to climate change and contribute to sustainable land use
9	Mexico	Programa nacional forestal 2020–2024	Prevent soil erosion, and promote the conservation of natural resources

7 Conclusion and Future Discussion

In conclusion, Regenerative agricultural Farming Practices have offered a promising solution for controlling soil erosion and promoting long-term environmental sustainability. The practices such as cover cropping, no-till farming, crop rotation, Agroforestry, Intentional/Rotational Grazing, mulching, etc., when adopted alone or along in combination, helped in improving the structure and health of the soil, preventing soil erosion & enhancing overall ecological biodiversity. Through the implementation of these practices, farmers could withstand the negative impacts of extreme weather events and improve crop yield over the years. The experimental, case studies and real-life examples have shown the importance of adopting these regenerative practices on a broad scale.

Governments, NGOs, Policymakers, and researchers should support and promote the adoption of these practices by educating the benefits to the farmers, making policies and guidelines for successful implementation, conducting workshops and training programming programs, and providing incentives for farmers who converted from conventional agricultural practices to regenerative agricultural practices. Additionally, continued research and innovations are essential for fine-tuning and adopting these techniques across the world with diverse topographies. This book chapter demonstrates how regenerative agriculture has the potential to transform land management techniques and establish a more harmonious relationship between humans and the Earth's valuable resources. Regenerative agriculture has shown more significant potential for controlling soil erosion and promoting soil quality. These practices have not reached their full potential as they are currently adopted as a method of trial and error to protect soil health from deterioration. As the concept of regenerative agriculture evolves, there are various essential areas and key features that will be researched more in the future. These can be critical to the creation of long-term plans for the promotion of sustainable agriculture systems across the world.

Researchers should mainly focus on refining erosion control practices by exploring all the possible combinations of regenerative agricultural techniques that are suitable according to the topography of the soil available and enhancing the effectiveness of these practices as a whole for better yield and productivity. They should also consider the long-term consequences of these behaviour combinations to determine if there are any potential hazards or restrictions. They need to focus on how these practices are performing and adopting different climatic conditions such as droughts, temperature fluctuations, downpours, storms, etc., and how this impact mitigating soil erosion. They should also concentrate on the scale at which these practices can be implemented in order to achieve maximum productivity. New collaboration and the exchange of information have to be encouraged in order to spread these practices among farmers across the continents. These discussions are crucial for promoting and implementing these regenerative agricultural practices in order to promote soil growth, control erosion factors, and maintain sustainable land management practices across the globe.

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Advantages and Disadvantages of Soil Regeneration

G. A. Abubakar, A. I. Gabasawa, L. A. Sale, and D. N. Obemah

Abstract *Soil regeneration* generally focuses on soil restoration and improving its quality in order to improve plant growth and crop yields without degrading the soils. Soil regeneration improves not only its sustainability but also tends to improve its water quality and protect the soil against erosion through runoff. Some of these techniques used for soil regeneration are cover cropping, crop rotation, zero till or minimal tillage, reducing soil disturbance, mulching, and integrated nutrient management (INM). These practices have many promising benefits, which include carbon sequestration and reducing the use of fossil fuels. In less than a decade, we've seen soil regeneration through regenerative farming, providing solutions to soil deterioration and future of farming system for the increasing world population. For example, in Singapore, Soil regeneration enables Singaporeans to have the capacity to not just know and appreciate food but also grow their own without soil deterioration. Despite the clear benefits of this, such as mitigating emissions, improved soil fertility, higher nutrient use efficiency, biodiversity conservation, and improved long-term farmer livelihoods. It's still not growing fast enough, this is alarming because the solutions to our problems are available through our traditional conservation farming methods and we don't need to reinvent the wheel.

Keywords Soil regeneration · Soil health · Soil degradation · Soil conservation · Regenerative farming

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1 Introduction

Soil regeneration is a continuous process of improving the soil quality through the traditional conservational farming methods by supplying organic matter, which improves water retention and nutrient supply for crops. Soil regeneration ensures appropriate returning of soil nutrients that were lost either due to continuous cultivation in order to maintain soil fertility and productivity [1]. Soil degradation are mainly due to overgrazing, over-use of pesticides and fertilizers, inappropriate irrigation practices, continuous over cultivation and poor drainage, hence the need for soil restoration which not only reverses the negative effects of soil degradation but also leads to numerous benefits that enhance the overall soil quality. Soil regeneration farming is a way forward that will ensures the soil quality improvement which enhances crop yields [13]. It is also part of sustainable agriculture, which requires soil organic matter build up, erosion control, retention of soil nutrients increase and water retention, improve soil structure and create more diverse soil organisms [7]. Regenerative farming system is a shift or adjustment from modern-day agricultural farming system towards a sustainable farming practices [5] as shown Fig. 1.

Many studies have led us to conclude that the following are the fundamental tenets of soil regeneration. The main goal of soil regeneration is to improve and maintain the soil quality by increasing water retention and nutrients [13]. This can be achieved in many ways: addition of organic matter, planting of cover crops agroforestry to protect the top soils from water and wind erosion even during fallow periods or

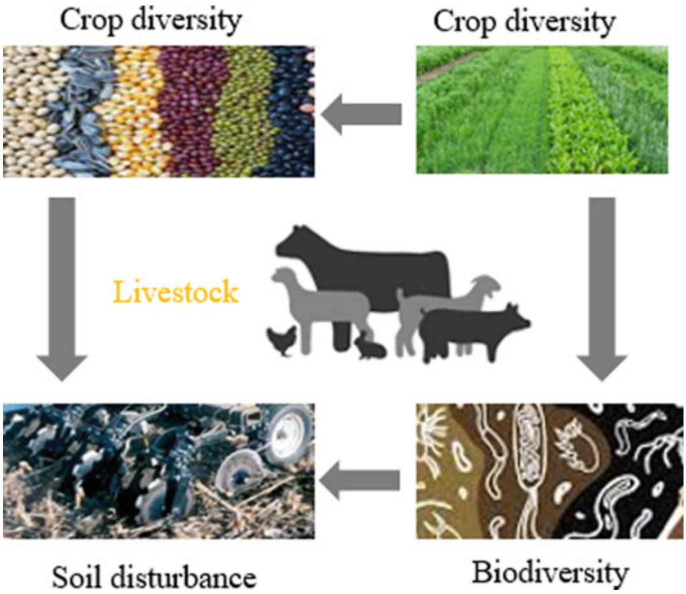

Fig. 1 Benefits of Soil regeneration farming

Table 1 Soil regeneration Practices

Management regime	Farm management practices
Cropland management	Cover cropping
	Agroforestry
	Crop rotation
	Mixed cropping
	Mixed farming
	Minimizing chemical inputs
	Rotational grazing
Soil management	Zero tillage
	Mulching
	Fertilizer management
	Drainage
	Composting

through zero or minimal tillage to avoid soil disturbances, maximizing biodiversity and planting diverse crops or mixing cereals and legumes through mixed cropping or crop rotations. Some of these cropland and soil management practices are listed (Table 1).

There are several factors both biotic and abiotic that causes soil degradation which resulted in soil fertility decline. These also makes soils lost its value in terms of nutrients for plants growth and development**.** Some of these factors are listed (Table 2).

Furthermore, these agricultural management practices are exacerbated through human activities over the years especially in Africa, leading to soil degradation, which requires soil regeneration practices for improving better crop yields and minimal soils disturbance, making healthier and better soils. Soil regeneration practices improves soil moisture conditions especially for plants in the drier areas during droughts [7].

Table 2 Soil degradation practices

Management regime	Farm management practices
Soil degradation causes	Monoculture
	Bush burning
	Deforestation
	Continuous cultivation
	Over grazing
	Intensive tillage
	Excessive use of pesticides
	Fertilizer management
	Over-irrigation
	Nature of organic material

Soil regeneration presents a challenge to farmers in terms of enhancing soil health as it stands today. They make and increase the available soil nutrients for plants growth and development**.** Some of these advantages and disadvantages of soil regeneration practices include.

2 Advantages of Soil Regeneration Practices

Soil regeneration strive to actively alter farming practises by boosting biodiversity, enriching soils, strengthening watersheds, and improving the wellbeing of livestock and wildlife [5]. By adopting a more comprehensive approach, they enhance their farms' ability to withstand harsh weather conditions and the effects of climate change, so contributing to the sustainability and vibrancy of their rural communities. The goal of the soil regeneration is to revitalise the traditional mixed-farm model by including various components on the farm, which is a crucial factor in the food sector [13]. Farmers can lower external inputs and outputs and thereby lower the danger of contamination by growing a wider variety of foods on one location.

Soil regeneration is changing the narrative and reviving the traditional and modern-day agricultural approach to sustainable agriculture and is promising which tends to show how these can help mitigate climate change, restore ecologies, improve soil health, resource use efficiency, enhance economic development, and improve long-term farmer livelihood [6]. These make soil regeneration important because of some of these advantages;

2.1 Climate Change

Soil regeneration helps mitigate greenhouse emissions, sequesters carbon in large amount and improved resilience of crops to climate change [5]. Soil organisms from our mighty microbe's photosynthesis can help our soil carbon sink, reducing the negative impacts of climate change [8]. Soil regeneration is a way forward toward climate resilience, adaptation and mitigation. The frequent extreme weather conditions such as floods, drought, and rising temperatures, farmers are now adopting new soil regeneration practices in order to conserve and protect their soils to the impacts of climate change. These new practices make their soils to absorb and store more water during a flood, and these soil moisture are used to maintain water scarcity during a drought [11].

2.2 *Increased Productivity and Soil Health*

These are achieved by maintaining and improving soil fertility through addition of organic matter and increasing biomass production, thereby increasing nutrients availability reducing soil deterioration and increasing crop yields. Farmers noticed more moisture and dark-colored soil aggregates indicating humus availability, binding soil aggregate together with plant roots [3]. Soil tests and visual observations from soil regeneration practices indicate vibrant soil structure and microbial communities such as earthworms which revealed increase mineralization rate in soil, the foundation of healthy soils.

2.3 *Reduced Fertilizer Use*

Soil regeneration farming increases nutrient use efficiency (NUE), by reducing the fertilizer demand compared to conventional soil practice with depleted soils, regenerated soils function better with less fertilizer since they already have all the nutrients required for plant growth. This is possible through the increase abundance of flora and fauna in soils. Increasing organic matter content and decomposition, enhances crop yield and optimizes, and reduces the pressure on our freshwater reserves [16].

2.4 *Biodiversity*

Soil regeneration practices can reduce biodiversity losses especially the flora. This can improve their abundance and reduced pesticide usage through biological control. This enhance biodiversity in soils through protecting their natural habitat and maintaining ecological balance [1]. **Biodiversity** losses is on the increase both in soils and water. Insect abundance visual observations indicate a richer and more diverse plant life returning to soils, which are a good signs of ecosystems returning to normal.

2.5 *Water Quality*

Soil regenerative farming also improves **water quality**. Less toxic and non -toxic chemical and pesticide used on regenerative farming practices indicate less or minimal chemical pollution impacting on ground and surface water. Reduction on the use of synthetic nitrogenous fertilizers can also reduce harmful algal infestation and leaching of nitrate in to the underground waters and less of water pollution [7]. Improving water quality will also improve better soil health by reducing soluble salts and heavy metals concentration in soils.

2.6 Prosperity

Soil regeneration practices improves farmer livelihood and standard of living. These can be possible through reduction in the cost of inputs, such as fertilizers, pesticides, cost of land preparation, and improved crop yield and crop quality, and greater resilience to market and extreme weather events. It also serve as good avenue to farmers on carbon trade which opens of new revenue by paying them for carbon capture and storage in the soil [2].

2.7 Erosion Control

Soil regeneration farming helps plants absorb more water and nutrients, which promotes higher growth. This enables them to enlarge and become more robust, enhancing their root architecture, eliminating the need for them to be concerned about being carried away by rainstorms or blown over by the action of wind and protect the soil from erosion.

2.8 Economic Benefits

Soil regeneration practices were a major motivator for many by improving overall soil quality and yields of crops than the traditional or modern-day agricultural practices. [14]. It reduced the cost of use of agro-chemicals, fertilizers, herbicides, pesticides as well as land preparation. Farmers livelihood improves when financial success is achieve easier through having access to healthy soils. Soil regeneration practices can **enhance rural economic development**. The idea behind soil regeneration is to generate wealth and life, make things easier and easily practicable for farmers across different soil operational systems that contribute to sustainable agriculture and environmental conservation. Although it’s not simple, there are effective methods for improving soil regeneration that can alter farmers’ perspectives and help them benefit from their labours [4].

3 Disadvantages of Soil Regeneration

There are numerous possible disadvantages in relation to soil regeneration through regenerative agriculture. There is always a catch, though, just like with anything. Merely “sustaining” our ecosystems may not be sufficient to counteract climate change and guarantee the long-term productivity of farming, considering the harm already done to the environment.

But in order to implement soil regeneration successfully, many farmers will need to pick up new abilities and expertise, especially in the area of soil management. Controlling farmers' expectations for outcomes may be challenging because proponents have been accused of making excessive claims about yield and advantages by sceptics. Farmers can reduce soil erosion in some areas and save between thirty and forty percent of their time by not tilling the soil, but regenerative agriculture often comes with undesirable drawbacks [12].

Farmers will have to pick up new abilities and information. Not tilling as much could result in more unwanted plants. Some farmers use more herbicides to make up for it. Reduced yields could occur, depending on the crop and regional circumstances, and the move away from traditional techniques will take time. Thus, the following are regenerative agriculture's primary drawbacks:

3.1 Time-Consuming

Soil regeneration can be advantageous since it boosts farm productivity but also time consuming and laborious, because the effects take time to manifest. It may take years to establish the tenets and practises of soil regeneration, thus it will take some time before advantages are realised [10]. Many farmers will need to learn new innovations or specialized knowledge in order to efficiently practise soil regenerative processes, especially when it comes to soil management.

3.2 Difficulties to Practice on Large Scale

Large-scale soil regenerative farming is similarly challenging to implement. The amount of produce that can be raised at one time is restricted by the requirement for crop rotation. Furthermore, more acreage is needed for holistic grazing practises than for standard agriculture. For this reason, it is challenging to apply regenerative practises to produce crops in large quantities [15].

3.3 Organisation and Planning

Soil regeneration also necessitates extensive organisation and meticulous planning. To ensure crop rotations have the least possible impact on yields, they must be carefully planned. Adopting regenerative principles is far from simple; although expanding holistically through regenerative practises can be less labour intensive, the necessity for organisation is raised [9].

4 A Call for Action

Given the importance of soil regeneration for sustainable agriculture and environmental conservation, there is a need for concerted action at various levels. Farmers, policymakers, researchers, and consumers all have a role to play in promoting and supporting soil regeneration practices so need to put hands on deck to ensure fruitful achievement. Some key actions that can be taken include, although not limited to: Providing farmers with access to training programs, technical assistance, financial incentives, and resources to adopt regenerative practices that can help overcome barriers to implementation. Governments, at all levels, should develop policies and regulations that will sustainably incentivize and support soil regeneration practices. This may include financial incentives, subsidies, tax breaks, and the integration of regenerative agriculture principles into agricultural policies. In addition, enlightening consumers on the benefits of soil regeneration and promoting the demand for sustainably produced food can create market incentives for farmers to adopt regenerative practices.

5 Future Research Directions

While significant progress has been made in understanding the advantages and disadvantages of soil regeneration, there are still several areas that require further research. Some important future research directions include: conducting long-term studies to assess the sustained benefits of soil regeneration practices on crop productivity, soil health, carbon sequestration, water quality, and biodiversity. This will help to build a stronger evidence base for the long-term viability and effectiveness of regenerative practices. Investigating strategies for scaling up soil regeneration practices from individual farms to larger landscapes. Understanding the social, economic, and policy factors that influence the adoption and scalability of regenerative practices is crucial for widespread implementation and will also be of paramount importance. More so, exploring innovative technologies such as precision agriculture, remote sensing, and data analytics to optimize soil regeneration practices. Developing tools and techniques that can accurately assess soil health, monitor progress, and guide decision-making will enhance the efficiency and effectiveness of regenerative agriculture.

6 Conclusion

Soil regeneration offers several significant advantages that contribute to sustainable agriculture and environmental conservation. By improving soil health and fertility, it enhances crop productivity, less need for synthetic fertilizers and pesticides, increases soil water retention, promotes biodiversity, mitigates climate change through carbon sequestration, and improves overall ecosystem resilience. These benefits have far-reaching implications for food security, environmental sustainability, and human well-being. It is, however, important to acknowledge that there are also some disadvantages associated with soil regeneration. The initial investment in implementing regenerative practices can be high, thereby requiring changes in farming techniques and infrastructure. Also, the transition period from conventional to regenerative practices may result in temporary reductions in crop yields or financial returns. Furthermore, the effectiveness of specific regenerative practices may vary, of course depending on some factors as the soil type, environmental conditions, and agronomic management practices.

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Rural and Urban Development: Pathways to Environmental Conservation and Sustainability

Ojo Emmanuel Ige, Festus Rotimi Ojo, and Sunday Amos Onikanni

Abstract This comprehensive project focuses on the soil regeneration and with the theme of environmental conservation for sustainable rural and urban development. It examines the importance of balancing development with environmental conservation to ensure long-term sustainability. The work discusses various aspects of environmental conservation, including the preservation of biodiversity, protection of ecosystems, mitigation of climate change, and the availability of natural resources. It highlights strategies for environmental conservation, such as sustainable land management, community engagement, policy and governance, and technological innovations. The work explores the challenges faced in environmental conservation and presents solutions, including awareness campaigns, capacity building, and international cooperation. Moreover, it showcases case studies and success stories from around the world, with a particular focus on Nigeria, demonstrating the positive impact of environmental conservation on both rural and urban communities. Overall, this work emphasizes the significance of environmental conservation as a pathway to achieve sustainable rural and urban development, promoting a resilient and harmonious future.

1 Introduction

Soil regeneration refers to the process of restoring and improving the health and fertility of degraded soils. It involves adopting practices and techniques that enhance soil organic matter content, biodiversity, nutrient cycling, and overall soil structure. The goal of soil regeneration is to rebuild and replenish the natural capacity of the soil ecosystem to support plant growth and productivity, while also promoting

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environmental sustainability [66]. Soil is a precious natural resource that sustains life on earth. It serves as the foundation for agriculture, supporting the growth of crops that provide food, fiber, and fuel. However, decades of intensive farming practices, such as excessive tilling, heavy pesticide use, and monoculture, have taken a toll on soil health and productivity. Degraded soils result in decreased crop yields, increased vulnerability to pests and diseases, and contribute to environmental issues like erosion and water pollution. To address these challenges and ensure long-term agricultural sustainability, there is a growing interest in soil regeneration.

Soil regeneration refers to the process of restoring soil health and fertility by adopting practices that enhance its organic matter content, biodiversity, structure, and nutrient cycling capabilities. Unlike conventional agriculture, which often depletes the soil, soil regeneration seeks to rebuild and replenish the natural capacity of the soil ecosystem to support plant growth while minimizing negative impacts on the environment. This approach acknowledges the intricate relationships between soil organisms, plants, and the broader ecosystem, emphasizing the importance of a holistic and regenerative mindset. Soil regeneration is a multidimensional concept encompassing various principles and practices such as microbial communities, cover crops, no tillage, crop rotation, Agroforestry and regerative grazing. Microbial Communities**:** Soil regeneration recognizes the pivotal role of microbial communities, including bacteria, fungi, and mycorrhizal fungi, in soil health. These microorganisms play a crucial role in nutrient cycling, organic matter decomposition, and disease suppression [2]. Cover Crops**:** The use of cover crops, such as legumes and grasses, is a key strategy in soil regeneration. These crops protect the soil from erosion, enhance organic matter content, and fix nitrogen, reducing the need for synthetic fertilizers [30]. No-Till Farming**:** Soil regeneration encourages the adoption of no-till or reduced-till farming practices. These techniques reduce soil disturbance, preserve soil structure, and minimize carbon loss through erosion [32]. Crop Rotation**:** Crop rotation is a fundamental aspect of soil regeneration. It helps break pest and disease cycles, maintains soil fertility, and diversifies the plant species within an ecosystem [59]. Agroforestry: Incorporating trees and shrubs into agricultural landscapes through agroforestry practices can enhance soil regeneration by improving nutrient cycling, reducing wind and water erosion, and providing additional sources of income for farmers [51].

Regenerative Grazing: Soil health is not limited to croplands; it also extends to pastures. Regenerative grazing practices, such as rotational grazing and holistic management, can restore grassland soils by increasing plant diversity and carbon sequestration [84].

These principles collectively contribute to the overarching goal of soil regeneration: to create resilient and sustainable agricultural systems that not only increase crop productivity but also preserve and enhance the health of the soil ecosystem.

2 Importance of Soil Regeneration

2.1 Soil Health and Fertility

Soil regeneration aims to improve soil health, which encompasses a range of physical, chemical, and biological properties. Healthy soils support robust root development, efficient water infiltration and retention, and nutrient availability for plants. By focusing on soil fertility, farmers can improve crop productivity while reducing the need for synthetic fertilizers, which can have detrimental effects on water quality and biodiversity [66].

2.2 Climate Change Mitigation

Healthy soils play a crucial role in mitigating climate change. Regenerative practices, such as cover cropping and conservation tillage, enhance carbon sequestration in the soil. Increased soil organic matter helps store carbon dioxide, a greenhouse gas, and improves the soil's capacity to withstand extreme weather events like droughts and floods [64].

2.3 Water Management

Regenerative agriculture practices help improve water management on farms. By enhancing soil structure and increasing organic matter content, soils can retain more water, reducing runoff and improving water infiltration. This not only improves water availability for crops but also helps mitigate the risks of soil erosion and water pollution [53].

3 Major Practices for Soil Regeneration

3.1 Cover Cropping

Planting cover crops between main crop seasons helps protect the soil from erosion, enhances nutrient cycling, and improves soil structure. Cover crops also contribute organic matter to the soil when they are incorporated or left as residue [9].

3.2 The Significance of Conservation Tillage

The adoption of conservation tillage techniques, such as no-till or reduced tillage, plays a pivotal role in minimizing soil disruption, preserving soil integrity, and curbing erosion. These practices contribute to the retention of soil moisture and foster favorable microbial activity within the soil [27].

3.3 Crop Rotation and Diversification

Planting a diverse range of crops in rotation can break pest and disease cycles, improve nutrient cycling, and promote beneficial soil organisms. Crop rotation also helps manage weed populations without relying heavily on herbicides [85].

3.4 Composting and Organic Amendments

Adding compost and organic amendments to the soil increases organic matter content, improves soil structure, and provides essential nutrients for plant growth. Compost also supports the growth of beneficial microorganisms that contribute to soil fertility [11].

However, recent advances and research show that.

(i) Exploration of Soil Microbiome: Current scientific investigations have been concentrated on comprehending the influence of soil Microbiome on soil vitality and plant productivity. Research has revealed that varied microbial communities play a pivotal role in nutrient cycling, controlling diseases, and bolstering the overall robustness of soil. By implementing regenerative approaches that foster microbial diversity, it is possible to enhance soil functionalities and optimize crop yields [6].

(ii) Agroforestry Systems: Agroforestry, the integration of trees with crops or livestock, has gained attention as a regenerative practice. Agroforestry systems provide multiple benefits, including improved soil structure, increased organic matter, and enhanced biodiversity. The presence of trees in agroforestry systems promotes nutrient cycling, provides shade and windbreaks, and can even generate additional income streams for farmers [52].

(iii) Soil Monitoring and Precision Agriculture: Advances in technology have enabled more accurate and efficient soil monitoring, allowing farmers to make data-driven decisions for soil management. Techniques such as remote sensing, soil sensors, and digital mapping help assess soil health parameters, nutrient status, and moisture levels. Precision agriculture tools assist in optimizing inputs and reducing environmental impacts, thus supporting soil regeneration efforts.

(iv) Policy and Education Initiatives: Recognizing the importance of soil regeneration for sustainable agriculture, many countries and organizations have initiated policy measures and educational programs. These initiatives aim to promote the adoption of regenerative practices, provide financial incentives for farmers, and raise awareness about the benefits of soil health. Policy support and education play a crucial role in fostering the widespread adoption of soil regeneration practices [36].

Moreover, Soil regeneration is an essential approach for sustainable agriculture, offering a path towards restoring and improving the health of our soils. By implementing practices that enhance soil fertility, biodiversity, and structure, farmers can not only increase crop productivity but also mitigate climate change, improve water management, and protect the environment. Recent advances in understanding soil micro biomes, agroforestry systems, soil monitoring technologies, and supportive policy measures have further strengthened the prospects of soil regeneration.

By embracing regenerative practices and adopting a holistic approach to soil management, farmers can cultivate resilient and productive soils while safeguarding the long-term viability of agriculture. However, continued research, knowledge exchange, and collaboration among stakeholders are necessary to refine and expand the toolkit of soil regeneration practices, ensuring a sustainable and secure food future.

Soil regeneration has significant impacts on environmental protection by promoting sustainable agricultural practices and mitigating various environmental issues. Here is a detailed explanation of its impact on environmental protection.

i. Soil Erosion Prevention: Soil regeneration practices, such as cover cropping, conservation tillage, and agroforestry systems, help prevent soil erosion. These practices protect the topsoil from wind and water erosion, reducing sedimentation in rivers and lakes and preserving water quality [73]. By preventing soil erosion, soil regeneration contributes to the conservation of natural resources and the protection of aquatic ecosystems.

ii. Water Quality Improvement: Regenerative practices improve water quality by reducing nutrient runoff and the contamination of water bodies. Soil with enhanced organic matter and improved structure has higher water-holding capacity, reducing the risk of nutrient leaching [53]. Additionally, the adoption of regenerative practices reduces the need for synthetic fertilizers and pesticides, minimizing the potential negative impacts on water quality.

iii. Climate Change Mitigation: Soil regeneration plays a vital role in climate change mitigation by sequestering carbon dioxide from the atmosphere. Practices such as cover cropping, conservation tillage, and composting increase soil organic matter, which serves as a carbon sink [64]. Increased carbon sequestration in soils helps offset greenhouse gas emissions, contributing to the reduction of atmospheric carbon dioxide levels.

iv. Biodiversity Conservation: Soil regeneration practices support biodiversity conservation by promoting a healthy soil ecosystem. The enhancement of soil organic matter, microbial diversity, and beneficial soil organisms through regenerative practices fosters a favorable environment for a variety of organisms, including beneficial insects, earthworms, and microbial communities [27]. The preservation of biodiversity in soils is crucial for the functioning of ecosystems and the provision of ecosystem services.

v. Sustainable Resource Management: Soil regeneration promotes sustainable resource management by reducing reliance on external inputs. Practices like crop rotation, cover cropping, and composting improve soil fertility, reducing the need for synthetic fertilizers and chemical inputs [32]. This leads to a more sustainable use of resources, reducing the environmental impacts associated with their production and application.

vi. Water Conservation: Soil regeneration practices help conserve water by improving soil structure and water-holding capacity. Healthy soils with increased organic matter content can retain more water, reducing irrigation needs and improving water use efficiency [53]. This is particularly important in regions facing water scarcity and drought conditions, as soil regeneration can contribute to water conservation and sustainable water management [86].

vii. Enhanced Resilience to Climate Change: Soil regeneration practices enhance the resilience of agricultural systems to climate change impacts. Healthy soils are better equipped to withstand extreme weather events, such as droughts and heavy rainfall, due to their improved water infiltration and retention capacities [57]. By improving soil health and structure, soil regeneration helps farmers adapt to changing climatic conditions and reduces the vulnerability of agricultural systems to climate-related risks [72].

viii. Reduced Energy Consumption: Adopting soil regeneration practices can lead to reduced energy consumption in agriculture. For instance, conservation tillage practices that minimize or eliminate plowing reduce fuel usage and machinery operation time [9]. By reducing energy inputs, soil regeneration contributes to the mitigation of greenhouse gas emissions associated with agricultural activities [3].

ix. Soil Fertility Restoration: Soil regeneration focuses on restoring and improving soil fertility through organic matter enrichment. Organic matter serves as a nutrient reservoir, supporting plant growth and reducing the need for synthetic fertilizers [62]. By reducing the reliance on chemical fertilizers, soil regeneration practices mitigate the environmental impacts associated with their production and use, such as energy consumption, greenhouse gas emissions, and water pollution [3].

x. Long-Term Sustainability: Soil regeneration is integral to achieving long-term sustainability in agriculture. By prioritizing soil health and adopting regenerative practices, farmers can maintain the productivity of their land while minimizing negative environmental externalities. Healthy soils contribute to the overall sustainability of agricultural systems, supporting long-term food production, biodiversity conservation, and ecosystem stability [1].

4 Importance of Environmental Conservation

Environmental conservation plays a crucial role in achieving sustainable rural and urban development. It encompasses a range of practices and initiatives aimed at preserving and protecting natural resources, ecosystems, and biodiversity. The importance of environmental conservation cannot be overstated, as it directly impacts our well-being, quality of life, and the future of our planet. Some of the major reasons why environmental conservation is of utmost importance are:

(i) The Significance of Environmental Conservation in Safeguarding Biodiversity: Environmental conservation serves as a pivotal guardian of Earth's biodiversity, encompassing the remarkable diversity of life on our planet. Protected ecosystems offer shelter to a wide array of species, playing a vital role in upholding ecological equilibrium and furnishing invaluable ecosystem services [12]. The conservation of biodiversity is instrumental in preserving the stability of ecosystems, bolstering their resilience in the face of environmental fluctuations, and sustaining vital processes such as pollination, nutrient cycling, and natural pest control [46, 86].

(ii) The Intersection of Environmental Conservation and Climate Change Mitigation: Environmental conservation is intricately intertwined with efforts to mitigate climate change. Undisturbed ecosystems, including forests, wetlands, and oceans, function as crucial carbon sinks, effectively absorbing and retaining substantial quantities of carbon dioxide from the atmosphere [45].

(iii) Through the preservation and rejuvenation of these ecosystems, environmental conservation actively contributes to climate change mitigation by diminishing greenhouse gas emissions and advancing the process of carbon sequestration [16].

(iv) Protection of Natural Resources: Environmental conservation ensures the sustainable management and utilization of natural resources. Conserving forests, freshwater sources, soil, and minerals helps maintain essential resources for various sectors, including agriculture, energy, and industry [13]. Sustainable resource management practices, promoted through conservation efforts, aim to balance resource extraction with long-term environmental and socio-economic benefits.

(v) Ecosystem Services Provision: Environmental conservation safeguards the provision of vital ecosystem services that support human well-being. Ecosystem services include the provision of clean water, air purification, soil fertility, climate regulation, and recreational opportunities [63]. Conserved ecosystems function as natural infrastructure, providing invaluable services that contribute to human health, economic prosperity, and quality of life.

(vi) Resilience to Environmental Risks: Conservation enhances the resilience of ecosystems and communities to environmental risks and disturbances. Preserved ecosystems are better equipped to withstand and recover from natural disasters, such as floods, droughts, and storms [47]. Conservation measures, such as coastal protection through mangrove preservation, can mitigate the impacts of climate-related events and provide natural buffers against extreme weather events.

(vii) Biodiversity Preservation: Environmental conservation is vital for preserving biodiversity, which is crucial for ecosystem stability and resilience. Biodiversity loss has profound ecological and economic consequences. Recent studies highlight the importance of biodiversity conservation in maintaining ecosystem functions, supporting food security, and promoting human well-being [16].

(viii) Climate Change Mitigation: Environmental conservation is closely tied to climate change mitigation efforts. Conserved ecosystems, such as forests, wetlands, and mangroves, sequester carbon dioxide, help regulate climate patterns, and mitigate the impacts of climate change. Protecting and restoring natural habitats contribute to global climate goals, including reducing greenhouse gas emissions and enhancing carbon sinks [4, 31].

(ix) Protection of Natural Resources: Environmental conservation is essential for sustainable management and preservation of natural resources. Conservation practices, such as sustainable agriculture, responsible water management, and forest stewardship, help maintain the integrity of ecosystems while ensuring the availability of critical resources for future generations [24, 25, 90].

(x) Ecosystem Services Provision: Environmental conservation ensures the continued provision of vital ecosystem services, which are essential for human well-being and sustainable development. Recent studies emphasize the importance of intact ecosystems in providing clean water, regulating climate, supporting pollination, and enhancing resilience to natural disasters [8].

(xi) Human Health Benefits: Environmental conservation contributes to human health and well-being. Conserved natural areas provide opportunities for physical activity, stress reduction, and improved mental health [10]. Access to green spaces and contact with nature have been linked to various health benefits, including reduced rates of obesity, cardiovascular diseases, and mental health disorders.

(xii) Economic Value: Environmental conservation has significant economic value. Conserved ecosystems provide a range of goods and services, such as timber, fish, clean water, and tourism opportunities, which contribute to local and national economies [85]. Investing in conservation can yield long-term economic benefits through sustainable resource use, job creation, and the protection of natural assets.

(xiii) Cultural and Indigenous Importance: Environmental conservation is essential for preserving cultural heritage and indigenous knowledge systems. Many communities have deep cultural and spiritual connections to the land and ecosystems, and conservation efforts help protect their traditions, values, and ancestral territories [7]. Safeguarding biodiversity and ecosystems honors the cultural diversity and wisdom of indigenous peoples and local communities.

5 Strategies for Environmental Conservation

Strategies for environmental conservation encompass a range of approaches and actions aimed at protecting and preserving the environment. These strategies can be implemented at various levels, from individual practices to national policies. Some key strategies for environmental conservation are as follows:

(i) Protected Areas and Biodiversity Conservation: Establishing and effectively managing protected areas is a key strategy for conserving biodiversity and habitats. Protected areas can include national parks, wildlife reserves, and marine sanctuaries. They serve as havens for endangered species, preserve critical habitats, and provide opportunities for scientific research and education [19].

(ii) Sustainable Land and Resource Management: Adopting sustainable land and resource management practices is crucial for environmental conservation. This includes sustainable agriculture, agroforestry, responsible forestry, and efficient water management. These practices aim to minimize soil erosion, preserve water quality, and ensure the sustainable use of natural resources [42].

(iii) Ecosystem Restoration: Restoring degraded ecosystems is an important strategy for environmental conservation. This can involve reforestation, wetland restoration, and rehabilitation of degraded lands. Ecosystem restoration helps to enhance biodiversity, promote carbon sequestration, and improve the resilience of ecosystems to climate change [48].

(iv) Sustainable Fisheries and Marine Conservation: Implementing sustainable fisheries management practices and marine conservation measures are crucial for preserving marine biodiversity and ecosystem health. This includes establishing marine protected areas, implementing responsible fishing practices, and reducing by catch. A sustainable fishery management helps maintain fish stocks and supports the livelihoods of coastal communities [37].

(v) Environmental Education and Awareness: Promoting environmental education and raising awareness about the importance of conservation are critical strategies. Environmental education helps foster a sense of stewardship and empowers individuals to make sustainable choices in their daily lives. It plays a vital role in inspiring collective action and influencing policy decisions [87, 88].

NOTE: These strategies work together synergistically to promote environmental conservation. By establishing protected areas, adopting sustainable land and resource management practices, restoring ecosystems, implementing responsible fishing methods, and promoting environmental education, we can make significant strides in preserving biodiversity, protecting ecosystems, and ensuring the sustainable use of natural resources.

6 Community Engagement

Community engagement is a vital component of environmental conservation efforts. It involves actively involving and collaborating with local communities in decision-making processes, implementing conservation initiatives, and fostering a sense of ownership and responsibility towards the environment. Some of the key aspects of community engagement in environmental conservation include:

(i) Participation and Collaboration: Community engagement entails actively involving community members in conservation projects, planning, and decision-making processes. It is important to seek their input, perspectives, and traditional knowledge related to the local environment. Collaborative partnerships between conservation organizations, local communities, indigenous groups, and other stakeholders help ensure that conservation efforts are culturally sensitive, inclusive, and effective.

(ii) Capacity Building: Building the capacity of local communities is crucial for effective environmental conservation. This involves providing education, training, and resources to empower communities to actively participate in conservation activities. Capacity building initiatives may include workshops on sustainable resource management, biodiversity monitoring, sustainable agriculture techniques, and alternative livelihood options. By equipping communities with the necessary skills and knowledge, they can become stewards of their local ecosystems [94].

(iii) Sustainable Livelihoods: Environmental conservation should consider the socio-economic well-being of local communities. Engaging communities in sustainable livelihood initiatives that are compatible with conservation goals can help alleviate poverty and reduce unsustainable resource use. This may involve promoting eco-tourism, sustainable agriculture practices, community-based forestry, or supporting the development of environmentally friendly enterprises. By linking conservation with economic opportunities, communities are more likely to support and actively participate in conservation efforts.

(iv) Traditional Ecological Knowledge: Recognizing and respecting the traditional ecological knowledge held by indigenous peoples and local communities is essential for successful conservation. Traditional knowledge systems often hold valuable insights into ecosystem dynamics, biodiversity, and sustainable resource management practices. Engaging with indigenous groups and local communities in a culturally sensitive manner allows for the integration of traditional knowledge alongside scientific approaches, leading to more holistic and effective conservation strategies [78].

(v) Environmental Education and Awareness: Promoting environmental education and raising awareness within local communities are integral parts of community engagement. Environmental education programs can help community members understand the importance of biodiversity, ecosystem services, and the impacts of human activities on the environment. By fostering environmental literacy and promoting sustainable behaviors, individuals become active participants in conservation efforts and advocates for positive change.

Community engagement in environmental conservation ensures that conservation efforts are inclusive, culturally appropriate, and address the needs and aspirations of local communities. By involving communities as active partners and stakeholders, conservation initiatives are more likely to be successful, sustainable, and have long-lasting impacts on both the environment and the well-being of local communities.

Additional information to supplement the points on community engagement in environmental conservation include:

(a) Social Justice and Equity: Community engagement should prioritize social justice and equity, ensuring that all community members, including marginalized groups, have a voice and equal opportunity to participate in conservation initiatives. It is important to address power imbalances, respect cultural diversity, and consider the needs and rights of all community members. Engaging with local communities in a fair and equitable manner helps build trust, foster social cohesion, and promote sustainable outcomes.

(b) Co-Management and Co-Governance: Co-management and co-governance approaches involve sharing decision-making authority and responsibilities between local communities and conservation organizations or government agencies. These collaborative frameworks recognize the rights, knowledge, and expertise of local communities in managing natural resources and conservation areas. By engaging in co-management processes, communities can actively participate in decision-making, monitor resource use, and contribute to the long-term sustainability of their environments.

(c) Conflict Resolution and Mediation: Community engagement in environmental conservation may involve addressing conflicts and competing interests. Conflicts can arise due to differing perspectives on resource use, land rights, or conservation goals. Implementing conflict resolution mechanisms and engaging in mediation processes can help find mutually beneficial solutions, foster dialogue, and build consensus among stakeholders. It is important to facilitate open and respectful communication to bridge differences and find common ground.

(d) Long-term Relationships and Trust Building: Building long-term relationships and trust with local communities is fundamental to successful community engagement in conservation. It requires sustained efforts, open communication, transparency, and demonstrating tangible benefits from conservation initiatives. Establishing trust enables collaborative decision-making, encourages community ownership, and enhances the likelihood of community support and long-term commitment to conservation efforts.

(e) Monitoring and Evaluation: Monitoring and evaluating the outcomes and impacts of community engagement activities are essential for adaptive management and continuous improvement. Regular assessment helps determine the effectiveness of community engagement strategies, identify areas for improvement, and learn from past experiences. It allows for the refinement of approaches based on feedback from community members and ensures that engagement efforts remain responsive to evolving community needs and aspirations [68].

(f) These additional points emphasize the importance of social justice, co-management, conflict resolution, trust building, and ongoing monitoring and evaluation in community engagement for environmental conservation. By integrating these aspects into conservation initiatives, we can foster meaningful partnerships, promote sustainable outcomes, and create positive social, economic, and environmental impacts within local communities.

7 Policy and Governances

Policy and governance play a crucial role in environmental conservation by providing a framework for decision-making, regulation, and implementation of conservation efforts. Here are some informations about policy and governance in environmental conservation which include:

7.1 Policy Development

Policies related to environmental conservation are developed at various levels, including international, national, regional, and local. These policies outline goals, guidelines, and regulations to protect and manage natural resources, biodiversity, and ecosystems [27]. They address issues such as land use planning, protected area management, wildlife conservation, sustainable resource utilization, and climate change mitigation and adaptation. Policy development involves scientific research, stakeholder consultations, and considerations of social, economic, and environmental factors [54].

7.2 Legal Frameworks and Regulations

Legal frameworks provide the basis for implementing environmental conservation policies. They include laws, regulations, and enforcement mechanisms to ensure compliance with conservation objectives. These frameworks establish rules for activities such as land use, wildlife trade, habitat protection, pollution control, and natural resource extraction. Effective enforcement and monitoring of regulations are essential to deter illegal activities and ensure the implementation of conservation measures [22, 96].

7.3 Global Environmental Conservation Through International Agreements and Conventions

The global landscape of environmental conservation is profoundly influenced by international agreements and conventions. Notable examples encompass the Convention on Biological Diversity (CBD), the United Nations Framework Convention on Climate Change (UNFCCC), and the Ramsar Convention on Wetlands. These pivotal accords facilitate international collaboration, set forth objectives and obligations, and champion the preservation and sustainable utilization of natural resources and ecosystems on a global scale [69].

7.4 Stakeholder Engagement

Effective governance involves engaging a range of stakeholders, including government agencies, non-governmental organizations (NGOs), indigenous groups, local communities, businesses, and scientists. Stakeholder engagement ensures that diverse perspectives are considered in decision-making processes, increases the legitimacy and effectiveness of policies, and fosters ownership of conservation initiatives [77]. Engaging stakeholders promotes transparency, inclusivity, and collaborative problem-solving.

7.5 Adaptive Management

Adaptive management approaches recognize the complexity and uncertainty of environmental systems. They involve iterative and flexible decision-making processes that incorporate feedback and learning from monitoring and evaluation. Adaptive management allows for adjustments to conservation strategies based on new information and changing circumstances. It promotes adaptive governance, where policies and actions are continuously refined based on scientific knowledge and stakeholder input [29].

7.6 Financial Mechanisms

Funding mechanisms and incentives are essential for supporting environmental conservation. Governments, international organizations, and private entities provide financial resources for conservation initiatives through grants, funding programs, and innovative financing mechanisms. These mechanisms can include payments for ecosystem services, biodiversity offsets, and green finance initiatives. Financial support helps implement conservation actions, support local communities, and facilitate sustainable economic development [38].

Policy and governance frameworks provide the necessary structure and mechanisms to guide and implement environmental conservation efforts. By developing effective policies, ensuring compliance with regulations, engaging stakeholders, and employing adaptive management approaches, governments and organizations can create an enabling environment for successful conservation outcomes. Collaboration between stakeholders and the integration of scientific knowledge are crucial for shaping policies and governance structures that address the complex challenges of environmental conservation.

8 Challenges and Solution

Some of the challenges and potential solutions in environmental conservation include:

Challenges

8.1 Habitat Loss and Fragmentation

i. Biodiversity Decline**:** Habitat loss and fragmentation pose significant threats to biodiversity, as they result in the destruction, reduction, or division of natural habitats, thereby diminishing the availability of suitable habitats, food sources, and mating opportunities for numerous species [96].
ii. Genetic Isolation**:** Fragmentation can lead to genetic isolation within populations of the same species, ultimately reducing genetic diversity and potentially rendering these populations less adaptable to environmental changes [35].
iii. Altered Ecosystem Functions: Natural habitats serve as the foundation for crucial ecosystem services, such as water purification, carbon sequestration, and pollination. Habitat loss and fragmentation disrupt these services, with far-reaching consequences for both ecosystems and human well-being [29].

Solution

i. Habitat Restoration: Efforts to restore degraded habitats and reconnect fragmented landscapes through initiatives like reforestation, wetland restoration, and the removal of barriers (e.g., roads or dams) are essential for mitigating habitat loss and fragmentation [17].
ii. Protected Areas: Establishing and expanding protected areas, including national parks and wildlife reserves, is a fundamental strategy to conserve

critical habitats and safeguard endangered species [50]. The effectiveness of these areas relies on proper management and enforcement [95].

iii. Land Use Planning: Effective land use planning and zoning regulations play a crucial role in minimizing habitat loss and fragmentation by identifying and safeguarding areas of high conservation value [72].
iv. Corridor Creation: The establishment of wildlife corridors or greenbelts between fragmented habitats facilitates species movement between isolated patches, preserving genetic diversity and ecological connectivity [5].
v. Sustainable Practices: Promoting sustainable land-use practices, such as agro forestry, sustainable logging, and urban green spaces, offers effective means to address habitat loss and fragmentation while supporting human needs [27, 40, 76].
vi. Public Awareness and Education: Raising public awareness about the significance of habitat conservation and the consequences of habitat loss and fragmentation is instrumental in garnering support for conservation initiatives and informed decision-making [55].
vii. International Collaboration: Given the transboundary nature of many species, international cooperation through agreements and treaties is critical for addressing habitat loss and fragmentation on a global scale [19].
viii. Addressing habitat loss and fragmentation necessitates a multifaceted approach that combines strategies to protect, restore, and reconnect habitats, fostering the long-term survival of ecosystems and the species they harbor [34].

Challenges

8.2 Climate Change

Climate Change Mitigation and Adaptation**:** Addressing climate change is a fundamental aspect of environmental conservation. Strategies for climate change mitigation focus on reducing greenhouse gas emissions through actions like transitioning to renewable energy sources, promoting energy efficiency, and reforestation. Climate change adaptation strategies aim to prepare ecosystems and communities for the inevitable impacts of climate change, such as rising temperatures, sea-level rise, and extreme weather events. This can include enhancing the resilience of natural habitats, implementing sustainable water management practices, and developing climate-resilient infrastructure [43]. Combating climate change is integral to preserving ecosystems and biodiversity in the face of a changing climate.

i. Rising Temperatures and Extreme Weather Events: Climate change is leading to an increase in global temperatures and a rise in the frequency and intensity of extreme weather events such as hurricanes, heatwaves, and wildfires [45]. These events can have devastating impacts on ecosystems and wildlife.

ii. Sea Level Rise: As a result of melting polar ice caps and the thermal expansion of seawater, sea levels are rising, threatening coastal habitats and communities [14]. Coastal ecosystems like mangroves and coral reefs are particularly vulnerable.
iii. Ocean Acidification: Increased levels of atmospheric carbon dioxide (CO2) are being absorbed by the oceans, leading to ocean acidification. This harms marine life, especially organisms with calcium carbonate shells or skeletons, such as corals and some plankton species [18].
iv. Loss of Biodiversity: Climate change disrupts ecosystems and can lead to shifts in species distribution and migration patterns [73]. Some species may not be able to adapt or move quickly enough, resulting in biodiversity loss.

Solution

i. Mitigation: Mitigation strategies aim to reduce greenhouse gas emissions to slow down or stop climate change. This includes transitioning to renewable energy sources, improving energy efficiency, and implementing carbon pricing mechanisms [44].
ii. Adaptation**:** Adaptation strategies involve making adjustments to ecosystems and human communities to better cope with the impacts of climate change. This can include restoring and protecting natural habitats that serve as buffers against extreme events and sea-level rise [20].
iii. Conservation of Carbon-Rich Ecosystems**:** Preserving and restoring carbon-rich ecosystems like forests, peatlands, and wetlands can help sequester carbon dioxide and reduce atmospheric carbon levels [33].
iv. Protecting Marine Ecosystems**:** Implementing marine protected areas and sustainable fishing practices can help safeguard marine biodiversity and reduce the stressors that contribute to ocean acidification [39].
v. Promoting Sustainable Agriculture**:** Sustainable agricultural practices, such as no-till farming and agroforestry, can reduce emissions from the agriculture sector and enhance soil carbon sequestration [83].
vi. Education and Awareness: Raising public awareness about climate change and its impacts on the environment is crucial for garnering support for conservation efforts and influencing individual behaviors [67].
vii. International Cooperation**:** Global cooperation is essential in addressing climate change. International agreements like the Paris Agreement provide a framework for countries to work together to limit global warming [90]. Addressing climate change requires a multifaceted approach that combines efforts to reduce emissions, protect and restore ecosystems, and build resilience in both natural and human systems. These solutions can help mitigate the environmental challenges posed by climate change and contribute to the conservation of the planet's biodiversity and ecosystems.

8.3 Challenges Posed by Invasive Species

i. Soil Erosion: Invasive plant species can displace native vegetation, leading to reduced soil stability and increased susceptibility to erosion [28].
ii. Altered Soil Composition: Some invasive species can change soil chemistry, leading to nutrient imbalances and reduced soil fertility [94].
iii. Disruption of Soil Microorganisms: Invasive species can alter soil microbial communities, affecting nutrient cycling and soil health [92]
iv. Biodiversity Threat: Invasive species can outcompete native species for resources, disrupt ecosystems, and lead to the decline or extinction of native species [80]. This poses a significant challenge to maintaining biodiversity.
v. Economic Impact: Invasive species can cause substantial economic losses in agriculture, forestry, and fisheries by damaging crops, forests, and aquatic ecosystems [75]. These impacts can have far-reaching economic consequences.
vi. Human Health and Safety: Some invasive species, such as certain plants and animals, can pose health risks to humans by spreading diseases or causing injuries [60]. For example, invasive mosquito species can transmit diseases like Malaria, Zika and dengue fever.

Solution

i. Invasive Species Management: Implement invasive species control measures such as mechanical removal, herbicide application, and biological control to prevent their establishment and spread [90, 92].
ii. Native Plant Restoration: Restore native plant communities to outcompete invasive species and stabilize soil, preventing erosion.
iii. Soil Remediation: Use soil remediation techniques to restore soil fertility and composition in areas impacted by invasive species.
iv. Monitoring and Early Detection: Establish monitoring programs to detect invasive species in their early stages and take immediate action to prevent further spread [61].

Addressing invasive species in environmental-soil conservation is crucial to maintaining soil health and preventing soil degradation. These solutions can help mitigate the challenges posed by invasive species.

8.4 Pollution

i. Loss of Soil Fertility: Soil pollution can result in the loss of essential nutrients and beneficial microorganisms, leading to reduced soil fertility and decreased agricultural productivity [72].
ii. Contaminant Migration: Pollutants such as plastic materials, heavy metals, pesticides, and industrial chemicals can leach into groundwater, posing risks to drinking water supplies and aquatic ecosystems [41, 49].

iii. Ecosystem Disruption: Soil pollution can disrupt terrestrial ecosystems by affecting plant and animal populations, reducing biodiversity, and altering soil structure and composition [1].
iv. Human Health Concerns: Contaminated soil can pose health risks to humans through the ingestion of pollutants in crops or direct contact with contaminated soil [41, 56].
v. Over exploitation of natural resources
vi. Soil Erosion**:** Overexploitation of soil, often due to unsustainable agricultural practices, can lead to soil erosion, which results in the loss of fertile topsoil, reduced agricultural productivity, and degradation of ecosystems [65].
vii. Deforestation**:** The excessive cutting down of forests for timber, agriculture, and urbanization disrupts ecosystems, reduces biodiversity, and contributes to climate change through the release of stored carbon [15].
viii. Overfishing**:** Overfishing depletes fish stocks and disrupts marine ecosystems, affecting not only the fish populations but also the livelihoods of millions of people dependent on fisheries.
ix. Water Depletion**:** Over-extraction of water resources for agriculture, industry, and municipal use can lead to water scarcity, affecting ecosystems and communities [23].

Solutions

i. Implement soil remediation techniques, such as phytoremediation (using plants to remove contaminants), bioremediation (using microorganisms to degrade pollutants), and soil washing, to clean up contaminated soils [79].
ii. Sustainable Farming Practices**:** Promote sustainable agriculture practices, such as organic farming, reduced pesticide use, and crop rotation, to prevent further soil pollution and improve soil health [74].
iii. Waste Management**:** Implement proper waste disposal and recycling practices to minimize the release of hazardous materials into the environment [91].
iv. Contaminant Regulation**:** Enforce strict regulations on the use and disposal of pollutants, including heavy metals, pesticides, and industrial chemicals, to prevent soil contamination [22].
v. Soil Monitoring**:** Establish soil monitoring programs to assess the extent of soil pollution, track changes over time, and inform remediation efforts [81].
vi. Public Awareness and Education**:** Educate the public, farmers, and industries about the risks of soil pollution and the importance of responsible chemical use and waste disposal [55].
vii. Land Use Planning**:** Integrate soil health considerations into land use planning and zoning regulations to protect vulnerable areas from contamination [58]. Addressing soil pollution in environmental conservation is essential to maintaining soil health, supporting sustainable agriculture, and protecting ecosystems and human health. These solutions can help mitigate the challenges posed by soil pollution.

9 Case Studies and Success Stories

These are some case studies and success stories in environmental conservation.

1. Gashaka-Gumti National Park: Gashaka-Gumti National Park, situated in Taraba and Adamawa States, is Nigeria's largest national park. It encompasses a variety of ecosystems, including tropical rainforests, savannas, and montane forests. The park has implemented measures to combat illegal activities such as logging, hunting, and encroachment, resulting in the protection of wildlife and habitats [47].
2. Hadejia-Nguru Wetlands: The Hadejia-Nguru Wetlands in northeastern Nigeria are an internationally recognized Ramsar site and an essential habitat for migratory birds, including the endangered Eurasian spoonbill and African skimmer. Conservation initiatives, such as habitat restoration, water management, and community-led conservation projects, have played a crucial role in safeguarding this wetland ecosystem [21].
3. Lekki Conservation Centre: The Lekki Conservation Centre, located in Lagos State, is a nature reserve and biodiversity hotspot within an urban setting. It serves as an educational hub, promoting environmental awareness and conservation among visitors. The center is home to various wildlife species and features a canopy walkway that allows visitors to experience the forest ecosystem firsthand.
4. Omo Forest Reserve: The Omo Forest Reserve, located in Ogun State, is one of the last remaining fragments of Nigeria's once-vast tropical rainforest. Conservation efforts have been focused on combating illegal logging, protecting endangered species such as the Nigeria-Cameroon chimpanzee and white-throated monkey, and supporting sustainable livelihoods for local communities through agroforestry and eco-tourism initiatives [70].
5. Erosion Control and Land Rehabilitation in Southeast Nigeria: In response to the significant erosion challenges faced in southeastern Nigeria, various erosion control and land rehabilitation projects have been implemented. These projects involve the construction of erosion control structures, reforestation, and community-based land management practices. These initiatives aim to mitigate the effects of erosion, protect fertile agricultural lands, and restore degraded landscapes.
6. The conservation of the Iberian Lynx in Spain and Portugal: The Iberian Lynx is one of the world's most endangered cat species. Through concerted conservation efforts, including habitat restoration, captive breeding programs, and active monitoring, the population of Iberian Lynx has shown signs of recovery. Collaborative initiatives between government agencies, conservation organizations, and local communities have played a crucial role in conserving this critically endangered species [76].
7. The restoration of the Loess Plateau, China: The Loess Plateau in China faced severe soil erosion and land degradation due to unsustainable farming practices. In the 1990s, the Chinese government implemented the Grain for Green Program, which involved reforesting and restoring degraded lands. This massive ecological

restoration project has resulted in significant improvements in soil conservation, water retention, and biodiversity. The success of the Loess Plateau restoration serves as an inspiring example of large-scale land rehabilitation and sustainable land management [95].

8. The recovery of the California Condor population, USA: The California Condor is one of the world's most endangered bird species. Through captive breeding programs, intensive monitoring, and habitat protection, the California Condor population has experienced a remarkable recovery. The collaboration between government agencies, conservation organizations, and stakeholders has played a crucial role in ensuring the survival and continued growth of this iconic bird species [26].

These case studies and success stories demonstrate that with effective conservation strategies, collaboration among stakeholders, and a commitment to long-term sustainability, it is possible to achieve positive outcomes for the environment and endangered species.

10 Conclusions and Recommendation of the Study

10.1 Conclusion

In conclusion, the imperative pursuit of environmental conservation, with a keen focus on soil regeneration, stands as a linchpin in our journey towards sustainable rural and urban development, ultimately charting a pathway to a more resilient and promising future. Soil, often overlooked and underestimated, is a foundational resource that underpins the prosperity and well-being of both human societies and natural ecosystems. Its multifaceted role in supporting agriculture, sustaining biodiversity, mitigating climate change, and purifying water renders it indispensable to our existence.

Our contemporary world grapples with an escalating crisis of soil degradation, driven by factors such as industrial agriculture, deforestation, urbanization, and climate change. The consequences are dire, as eroded and depleted soils lead to decreased crop yields, increased food insecurity, compromised water quality, and the release of greenhouse gases into the atmosphere. In the face of these daunting challenges, soil regeneration emerges as a beacon of hope and a powerful solution.

Soil regeneration encompasses a holistic approach that seeks to rehabilitate and revitalize our Earth's life-giving skin. It encompasses a myriad of strategies, including organic farming practices, reforestation efforts, the reduction of chemical inputs, agro ecological methods, and the promotion of sustainable land management. These strategies aim not only to restore the health and fertility of the soil but also to enhance its capacity to sequester carbon, thereby combating climate change.

Moreover, soil regeneration is not solely a technical endeavor; it is deeply intertwined with social, economic, and cultural dimensions. It involves the engagement of local communities, farmers, policymakers, and scientists in a collaborative effort to implement innovative and context-specific approaches. Such collaboration fosters resilience at both the rural and urban scales, offering a promising vision for sustainable development.

In rural contexts, soil regeneration can empower farmers to transition away from destructive agricultural practices, ushering in an era of regenerative agriculture that conserves soil, conserves water, and increases crop yields. The benefits are multifaceted, leading to improved food security, enhanced rural livelihoods, and the safeguarding of rural landscapes.

In urban environments, soil regeneration can be harnessed to foster green spaces, urban gardens, and sustainable land use planning. These initiatives not only enhance the quality of life for urban residents but also provide essential ecosystem services, such as flood prevention, air purification, and urban heat island mitigation. The integration of soil regeneration into urban planning is a testament to the interconnectedness of rural and urban areas in the quest for resilience.

However, the pursuit of soil regeneration is not without its challenges. It requires a paradigm shift in our approach to agriculture, land use, and resource management. It demands investments in research, education, and policy reforms that prioritize soil health. It calls for a collective commitment to reevaluate our consumption patterns and to tread lightly on the earth.

In the end, the endeavor of soil regeneration is not merely an environmental call to action; it is a moral obligation to safeguard the foundation of life on our planet. It is a testament to our capacity as stewards of the Earth, entrusted with the responsibility to leave behind a world that is as bountiful and resilient as the one we inherited.

In embracing soil regeneration as a central pillar of our sustainable rural and urban development, we forge a resilient pathway towards a future where the Earth's soils are teeming with life, where food is abundant, and where rural and urban communities thrive in harmony with nature. This is the promise of soil regeneration, a promise we must uphold with unwavering commitment for the sake of generations yet unborn.

10.2 Recommendation

Based on the findings of this study, the following recommendations are put forth:

1. Invest in Research and Education: Allocate substantial resources to research and education initiatives centered on soil health and regeneration. Support scientific studies that explore soil biology, chemistry, and ecology to develop a deeper understanding of soil systems and how they can be restored and preserved. Promote educational programs that raise awareness about the importance of soil health from early childhood to higher education levels.

2. Promote Regenerative Agriculture: Encourage the widespread adoption of regenerative agricultural practices. Provide incentives, subsidies, and technical support to farmers transitioning from conventional farming methods to regenerative approaches. These practices include crop rotation, cover cropping, reduced tillage, and organic farming. Highlight the economic benefits of regenerative agriculture, such as increased soil fertility and resilience to extreme weather events.
3. Implement Sustainable Land Use Planning: Integrate soil health and regeneration into land use planning at local and national levels. Develop policies that prioritize soil conservation, reforestation, and green infrastructure in urban and rural areas. Encourage mixed land use that incorporates green spaces, urban gardens, and sustainable building practices to protect and improve soil quality in urban environments.
4. Reduce Chemical Inputs: Promote the reduction of chemical inputs in agriculture. Advocate for the responsible use of fertilizers and pesticides, emphasizing organic and natural alternatives. Implement regulations and taxation measures that discourage the excessive use of synthetic chemicals, which can harm soil biodiversity and water quality.
5. Support Soil Carbon Sequestration: Establish programs and incentives that encourage the sequestration of carbon in soil. Carbon farming practices, such as Agroforestry and afforestation, can significantly contribute to mitigating climate change while enhancing soil health. Carbon markets and payments for ecosystem services can provide financial incentives for farmers and landowners to adopt these practices.
6. Community Engagement and Training: Empower local communities with the knowledge and tools necessary for soil conservation and regeneration. Organize workshops, training sessions, and capacity-building programs that engage farmers, landowners, and community members in sustainable soil management practices. Foster community-based initiatives for soil testing, composting, and organic waste management.
7. Public–Private Partnerships: Encourage partnerships between government agencies, NGOs, businesses, and research institutions to jointly tackle soil regeneration challenges. Collaborative efforts can leverage diverse expertise and resources to develop innovative solutions and scale up successful practices. Public–private partnerships can also facilitate the dissemination of knowledge and technologies related to soil health.
8. Regulatory Reforms: Review and update existing environmental regulations to incorporate soil protection and regeneration objectives. Enforce stricter land use regulations to prevent soil erosion, deforestation, and urban sprawl. Implement zoning laws that prioritize the preservation of critical soil resources, such as wetlands and forests.
9. Incentivize Soil Testing and Monitoring: Create financial incentives for regular soil testing and monitoring on agricultural lands. Provide subsidies or tax breaks to farmers who regularly assess their soil quality and implement recommended

improvements. Soil testing can help tailor soil management practices to specific local conditions, maximizing the benefits of regeneration efforts.

10. International Cooperation: Engage in international cooperation and agreements related to soil conservation and regeneration. Collaborate with neighboring countries to address cross-border soil degradation issues and share best practices. Advocate for soil health as a global priority within the United Nations and other international organizations.
11. Consumer Awareness: Promote consumer awareness and responsible consumption patterns. Educate the public about the environmental impacts of their food choices and encourage support for sustainably produced and regeneratively farmed products. Labels and certifications for products with a positive soil impact can guide consumers toward making more environmentally conscious choices.
12. Implement sustained, ongoing monitoring initiatives designed to evaluate the success and adaptability of soil regeneration initiatives over an extended period**.**

Executing adaptive management strategies that allow for adjustments based on ongoing data and research findings. Recognize that soil regeneration is a dynamic process that requires continuous evaluation and adaptation.

By implementing these comprehensive recommendations, we can embark on a transformative journey toward soil regeneration. This endeavor not only promises to secure our food systems, mitigate climate change, and protects ecosystems but also holds the key to sustainable rural and urban development, ensuring a resilient and prosperous future for generations to come.

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Soil Microbiome in Nutrient Conservation for Plant Growth

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Abstract The soil microbiome, a diverse and dynamic community of microorganisms residing beneath our feet, plays a vital role in the conservation and cycling essential nutrients that are needed for the growth of plants. This chapter explores the intricate relationships between soil microorganisms and plants with focus on their collaborative efforts to maintain soil fertility and also sustain terrestrial ecosystems. In the complex web of interactions, nitrogen-fixing bacteria and mycorrhizal fungi emerge as key protagonists. Understanding of soil microbiome offers invaluable insights in the mechanisms underpinning nutrient conservation and availability for plants. Moreover, recent advances hold promises in optimizing agricultural practices, reducing reliance in chemical fertilizers and also enhancing crop reliance to environmental stresses through metagenomics and microbiome engineering. However, there are challenges which includes the vast diversity of soil microorganisms, dynamic nature of soil ecosystems, and ethical considerations surrounding microbiome manipulation. Nonetheless, the potential benefits from sustainable agriculture to ecosystem restoration, underscore the importance of continued research into the soil microbiome. In conclusion, soil microbiome is a hidden treasure beneath our feet that shapes the foundation of life on earth. As its complexities are unraveled, the opportunities to nurture greener, more food security and environmentally sustainable future will also be unveiled.

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1 Introduction

The soil is usually regarded as the earth's living skin that harbors diverse and dynamic microorganisms in the ecosystem known as soil microbiome. The intricate community that comprises bacteria, fungi, archaea, viruses etc. plays a pivotal role in regulating nutrient cycling and availability in terrestrial ecosystems [1, 2]. These microorganisms, which are largely invisible to man's naked eye, holds the key to sustaining life above the ground, especially for plants, since they are intimately linked to conservation of nutrient and the availability in the soil environment. Growth and productivity of plants are basically reliant on the availability of essential nutrients, including phosphorus, potassium, nitrogen and a range of micronutrients [5]. Traditionally, the focus has been on chemical fertilizers to supply these nutrients. Although this approach has raised concerns about environmental degradation, including groundwater contamination and soil health deterioration [6]. In this context, understanding the intricate relationship between the soil microbiome and nutrient conservation offers a promising avenue for sustainable agriculture and ecosystem management.

The soil microbiome contributes significantly to processes in nutrient cycling where organic matters are broken down and essential nutrients are released and made accessible to plants [4]. Some soil microorganisms form symbiotic relationships with plants thereby aiding in the uptake of nutrients, disease resistance and overall health of the plant [3]. The interaction that exists between plants and their microbial partners in the rhizosphere create a nutrient-efficient microenvironment that is crucial for the growth and development of crops and natural vegetation as illustrated in Fig. 2 [38].

Presently, there are pressing challenges such as global food security and environmental sustainability that is growing urgency to explore and harness the potential of the soil microbiome in nutrient conservation for plant growth. This topic holds promise not only for optimizing agricultural practices but also for mitigating the environmental impact of conversional fertilization methods. To delve deeper into this vital and fascinating study area, the mechanisms by which soil microorganisms contribute to nutrient conservation has to be uncovered and also explore their implications for sustainable plant growth.

In the sections below, we will delve into the diversity of the soil microbiome, the mechanisms underlying nutrient conservation and tangible impacts of a robust microbiome on plant health and growth. We will also explore the practical applications of this knowledge in agriculture alongside the challenges and future directions of research in this burgeoning field.

2 Diversity of Soil Microbiome

The soil is basically the utmost part of the earth on which plants grow. Here, we will consider a better definition as it relates to the topic. Soil is a complex and diverse ecosystem teeming with a wide variety of microorganisms including bacteria, viruses, fungi, protozoa and archaea. Each of these microbial groups play a crucial role in nutrient cycling within the soil. Below are the organisms and their functions in the soil.

1. **Bacteria**: Bacteria, are most abundant in the soil play vital roles as follows
- Abundance and Diversity: Bacteria are among the most abundant microorganisms in the soil with estimates of about 1 billion individual cells in a single ram of soil according to Fierer et al. [7].
- Role in Nutrient Cycling: Bacteria are involved in various nutrient cycling processes including nitrogen fixation aided by nitrogen fixing bacteria, nitrification aided by ammonia oxidizing bacteria and organic matter decomposition aided by decomposers like Actinobacteria and Proteobacteria [4].

2. **Fungi**: Fungi play the following roles
- Abundance and Diversity: Fungi which includes molds and yeasts are abundant in soil and they exhibit high diversity.
- Role in Nutrient Cycling: Fungi are critical and important in the breakdown of organic matters such as lignin and cellulose into smaller and simpler compounds via decomposition. The also form mycorrhizal associations with plants aiding in nutrient uptake especially phosphorus [8].

3 **Archaea**: Archaea play vital roles such as
- Abundance and Role: These organisms are less studied but they are increasingly recognized for their roles in nutrient cycling particularly in extreme environments. Some ammonia-oxidizing archaea contributes to nitrification [9].

4. **Viruses**: Viruses play the following roles
- Abundance: Viruses or bacteriophages are abundant in soil with estimates of up to 10 billion viral particles per gram of soil [10].
- Role in Nutrient Cycling: Viruses can influence microbial community composition and nutrient cycling by infecting and lysing bacterial and archaeal cells, releasing nutrients in the process [10].

5. **Protozoa**:
- Abundance and Role: Protozoa which includes amoeba and flagellates are micropredators in the soil ecosystem. These organisms feed on bacteria and release nutrients through their activities [11].

Roles in Nutrient Cycling: What are the roles microbes play in nutrient recycling? Now, having understanding of the roles these microorganisms play in nutrient cycling is crucial for sustainable agriculture and ecosystem management. The diverse microorganisms contribute greatly to nutrient cycling in several ways as listed below.

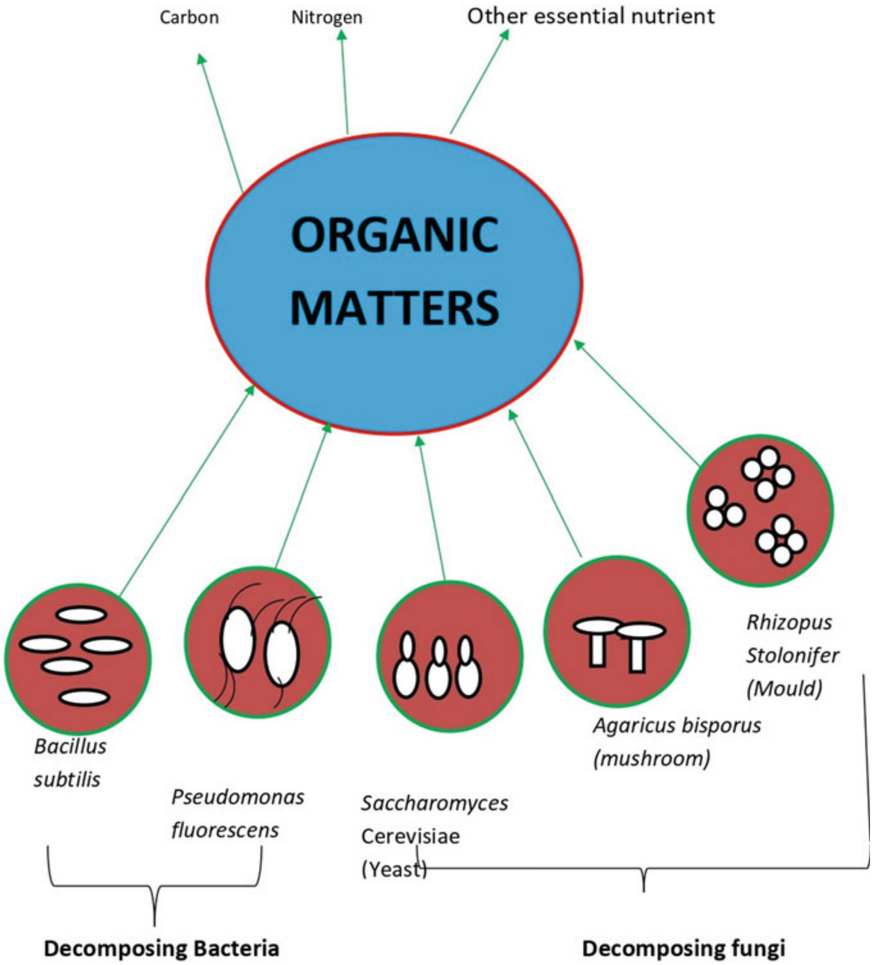

Fig. 1 Decomposition of organic matters to carbon, Nitrogen and other essential nutrient by soil microbes. *Source* Adapted from Nature Reviews Earth Environment) [38]

- **Decomposition**: Bacteria and fungi decompose organic matter releasing carbon, nitrogen and other essential nutrients. *Bacillus subtilis* and *Pseudomonas fluorescens* are examples of decomposer bacteria. Apart from bacteria being the most abundant organism in the soil, they are also common decomposers in nature as illustrated in Fig. 1 above. This is because, they are abundant in soil both in vegetative and dormant forms. Fungi such yeasts, mushrooms and molds are the main decomposers in many environments. Fungi have hyphae that are branching filaments that enables them to enter organic matters thereby making fungi effective decomposers.

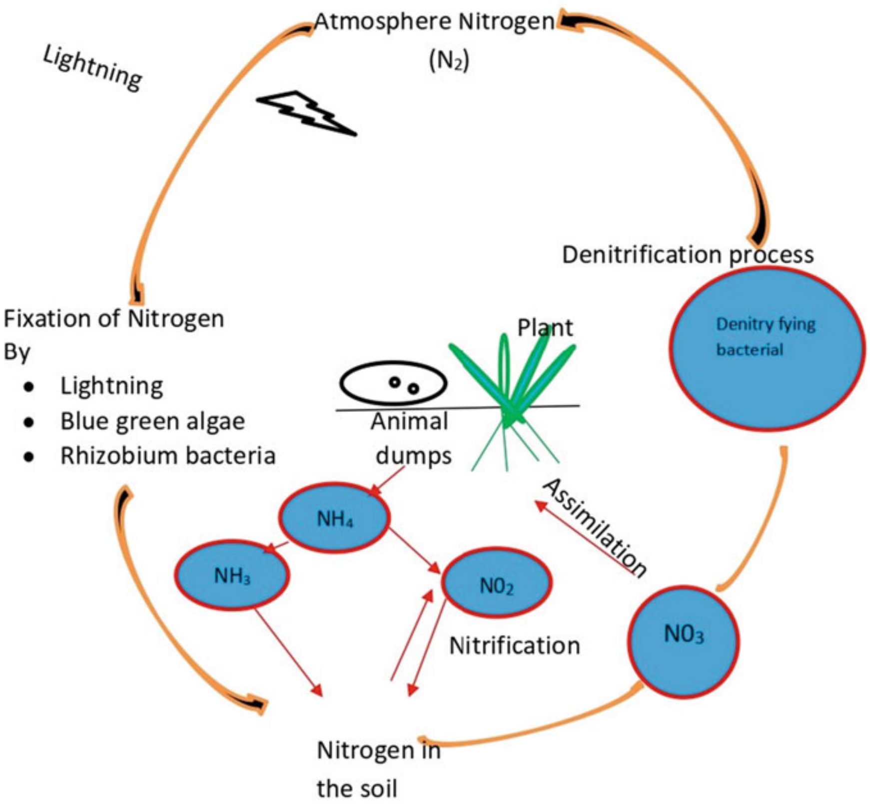

Fig. 2 Nitrogen cycle illustration. *Source*: reproduced from shutter stock) [37]

- **Nitrogen Cycling**: The nitrogen cycle is the biogeochemical cycle through which nitrogen is being converted into multiple chemical forms as it circulates within the atmospheric terrestrial and marine ecosystems. This can be done by physical and biological processes. Four processes are involved in nitrogen cycling through the biosphere and they are nitrogen fixation, decay, nitrification and denitrification. Bacteria such as *Rhizobium*, *Nitrosomonas*, *Nitrobacter* are some examples of bacteria used in nitrogen cycling. When we look at Fig. 2, labelled N_2 process biogeochemical explanation. It is an educational diagram showing denitrification, fixation, nitrification and assimilation in an ecosystem environment model [37].

- **Phosphorus Acquisition**: Mycorrhizal fungi help plants acquire phosphorus which is limited in the soil.
- **Carbon sequestration**: This is a process of storing carbon in a carbon pool. It is also a naturally occurring process that can be achieved with technology. Microbes also contribute to this process by storing carbon in soil organic matter [12].

3 Symbiotic Relationships Between Soil Microbes and Plants

A symbiotic relationship is an ongoing interaction that exist between organisms of different species. Thus, the symbiotic relationships between soil microbes and plants are as follows:

A. **Mycorrhizal Association**

Arbuscular Mycorrhizae (AM): Arbuscular mycorrhizal fungi from mutualistic relationships with the majority of plant species including many crops [8].

Ectomycorrhizae (ECM): Ectomycorrhizal fungi associates mainly with trees and some woody shrubs [8].

Role: In mycorrhizal associations, fungi extend their hyphae into plant roots, increasing the plants access to nutrients, particularly phosphorus and nitrogen in exchange for carbon compounds from the plant [8].

B. **Rhizobia and Leguminous Plants**

Symbiotic Nitrogen Fixation: Rhizobia bacteria establish symbiotic relationship with leguminous plants. They form nodules on plant roots where they fix atmospheric nitrogen into ammonia thereby, benefiting both the plant and the microbe [13].

C. **Endophytic Bacteria**:

Beneficial Bacteria: certain endophytic bacteria reside within plant tissues, enhancing plant growth, disease resistance and stress tolerance [14].

Nitrogen-Fixing Endophytes: Some endophytic bacteria can fix nitrogen providing an additional source of this essential nutrient to the host plant [15].

D. **Actinorhizal Symbiosis**:

Unique Associations: Actinorhizal plants form symbiotic relationship with actinomycete bacteria. This association is vital for the establishment of these plants in nutrient poor soils [16].

Role: Actinorhizal symbiosis allows plants to access fixed nitrogen, making them important contributors to soil nitrogen availability [16]. This symbiotic relationship illustrates how the soil microbe and plants cooperate to enhance nutrient uptake, improve plant health and confer resilience against environmental stressors.

4 Nutrient Conservation Mechanisms

Nitrogen Fixation:

- **Process**: Nitrogen fixation is the conversion of atmospheric nitrogen (N_2) into ammonia (NH_3) or other organic nitrogen compounds by certain microorganisms, particularly archaea and nitrogen-fixing bacteria [17].

- **Role**: Nitrogen-fixing microbes play a crucial role in making atmospheric nitrogen available for plants as a source of essential nutrients [18].

Nutrient Mineralization:

- **Process**: Nutrient mineralization is the conversion of organic matter, such as dead plant and animal materials into inorganic nutrients like nitrate (NO^{3-}), ammonium (NH^{4+}) and phosphate (PO^{4-}) by soil microorganisms through decomposition [19].
- **Role**: This process releases nutrients from organic matter, making them available for plant uptake and growth [19].

Organic Matter Decomposition:

- **Process**: Organic matter decomposition involves the breakdown of complex organic compounds such as cellulose and lignin, by a diverse range of microorganisms including bacteria and fungi [20].

These mechanisms highlight the critical roles of soil microorganisms in nutrient conversation within ecosystems. By fixing atmospheric nitrogen, mineralizing nutrients from organic matter and decomposing complex organic compounds. Microorganisms contribute significantly to nutrient availability for plants, thus sustaining terrestrial life.

5 Mechanisms that Contribute to Nutrient Availability for Plants and Their Impact on Plant Health and Growth

1. Nitrogen Fixation

Contribution to Nutrient Availability: Nitrogen fixation by symbiotic bacteria (for example Rhizobia) and free-living nitrogen-fixing bacteria increases the availability of nitrogen compounds such as ammonium (NH^{4+}) and nitrate (NO^{3-}) which are essential nutrients for plant growth [18].

Impact on Plant Health and Growth: Adequate nitrogen availability supports vigorous plant growth, improved chlorophyll production and overall plant health as nitrogen is a key component of amino acids, proteins and nucleic acids [18, 21].

2. Nutrient Mineralization

Contribution to Nutrient Availability: Nutrient mineralization transforms organic matter like decomposing plant residues, into inorganic forms of essential nutrients (examples include: nitrate, ammonium, phosphate) that are readily taken up by plants [19].

Impact on Plant Health and Growth: Nutrient mineralization enhances plant nutrient availability, leading to improved root and shoot growth, increased photosynthesis and overall plant productivity [19, 22]

6 Organic Matter Decomposition

Contribution to Nutrient Availability: Decomposition of organic matter by soil microorganisms release nutrients like carbon, nitrogen, phosphorus and micronutrients into the soil thereby making them accessible to plant roots [20].

Impact on Plant Health and Growth: Organic matter decomposition promotes plant health by providing a continuous supply of nutrients, improving soil structure, water-holding capacity and nutrient retention [23, 24].

Note: These mechanisms collectively enhance nutrient availability to plants ensuring they receive essential elements required for growth and development. A well-nourished plant exhibits increased resistance to stressors, better disease resistance and overall improved fitness, contributing to healthier ecosystems and sustainable agriculture.

7 The Role of Soil Microbiome in Enhancing Plant Resilience to Environmental Stressors

The role of soil microbiomes in enhancing plant resilience to environmental stressors is significant and multifaceted. Microorganisms in the soil play vital roles in helping plants to adapt and withstand various stressors such as drought, salinity, pathogens and nutrient limitations. Here is an overview of their roles.

Drought stress

Role: Certain soil bacteria and Mycorrhizal fungi form symbiotic relationships with plants that enhance their water-use efficiency and tolerance to drought stress [24].

Salinity Stress

Role: Halotolerant and halophilic microorganisms in the soil can mitigate the negative effects of high soil salinity by improving plant salt tolerance, maintaining ion homeostasis and promoting nutrient uptake [26].

Pathogenic Suppression

Role: Beneficial soil microorganisms including certain bacteria and fungi can suppress soil-borne plant pathogens by outcompeting or antagonizing them, producing antimicrobial compounds and inducing systemic resistance in plants [23].

Nutrient Stress

Role: Soil microorganisms including nitrogen-fixing bacteria and mycorrhizal fungi enhance nutrient availability to plants, helping them to overcome nutrient limitations and nutrient stress [8, 18].

Climate Change Resilience

Role: The soil microbiome can help plants adapt to changing climatic conditions by influencing their response to temperature, precipitation and CO_2 levels. Soil microorganisms can also store carbon, contributing to climate mitigation [27]. The soil microbiome is a critical ally for plants facing environmental stressors. These microbes assist plants in various ways from improving water use to suppressing pathogens and enhancing nutrient availability, ultimately bolstering plants resilience to challenging environmental conditions. This symbiotic relationship between plants and their microbial partners is vital for ecosystem stability and sustainable agriculture.

8 Agricultural Applications

How Understanding the Soil Microbiome Can Lead to Sustainable Agricultural Practices

Understanding the soil microbiome can indeed lead to sustainable agricultural practices by informing and optimizing farming techniques. A simple illustration of the applications of soil microbiomes for sustainable agricultural practices can be seen in Fig. 3. Here's an examination of how this knowledge contributes to sustainability.

- **Precision Agriculture**

  Role of Soil Microbiome: Understanding the composition and diversity of the soil microbiome can help identify areas with specific microbial communities that benefit crop growth.

  Impact: Precision agriculture allows for targeted interventions such as tailored fertilization and irrigation, minimizing resource wastage and reducing environmental impacts [28]

- **Disease Management**

  Role of Soil Microbiome: Knowledge of soil microbial communities helps identify beneficial microorganisms that can suppress plant pathogens through competition or antagonism.

  Impact: Implementing microbial-based disease management strategies reduces the need for chemical pesticides promoting environmentally friendly and sustainable agriculture [23].

- **Nutrient Management**

  Role of Microbiome: Understanding nutrient cycling by soil microorganisms helps optimize fertilizer use and also reduce nutrient runoff.

  Impact: Improved nutrient management practices minimize nutrient pollution, protect water quality and enhance nutrient use efficiency in agriculture [19]

- **Carbon Sequestration**

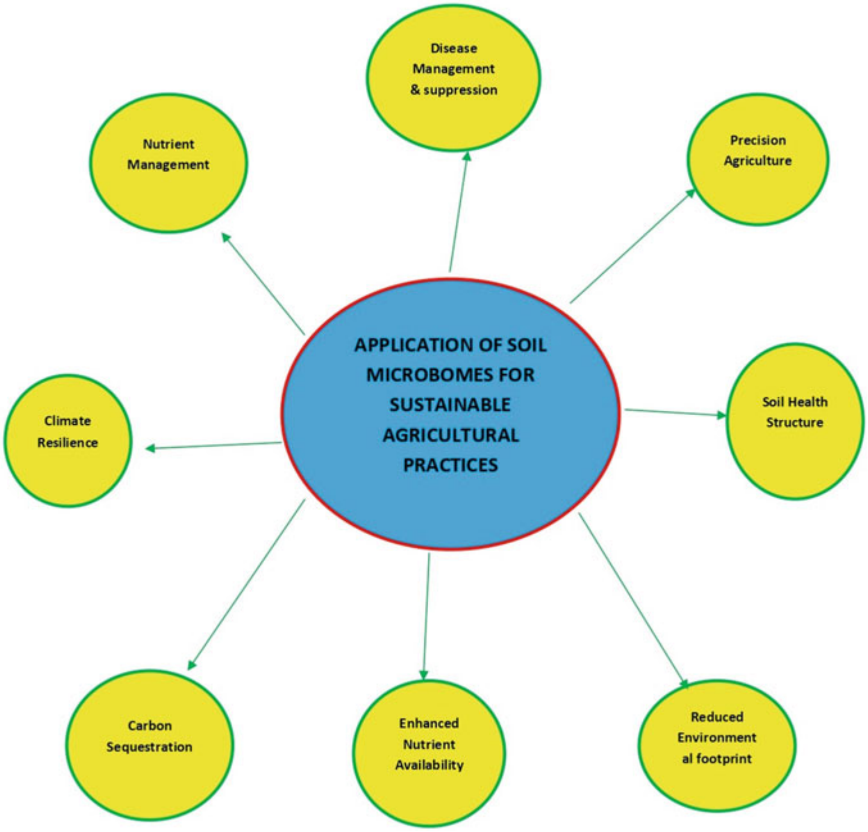

Fig. 3 Application of soil microbiomes for sustainable agricultural practices. (Reproduced from Nature) [12]

Role of Soil Microbiome: Soil microorganisms are key players in carbon cycling and sequestration.

Impact: Sustainable agriculture practices such as reduced tillage and cover cropping enhance soil carbon content, mitigating climate change and improving soil health [12].

- **Reduced Environmental Footprint**

Role of Soil Microbiome: Knowledge of the soil microbiome allows for the development of agricultural practices that reduce environmental impacts such as greenhouse gas emissions.

Impact: Sustainable farming practices contribute to reduced carbon emissions, increased carbon sequestration and overall lower environmental footprints [27].

Understanding that soil microbiome plays a pivotal role in shaping sustainable agricultural practices. This knowledge empowers farmers and researchers to adopt practices that are environmentally responsible, economically viable and supportive of long-term food security. By harnessing the power of soil microorganisms, agriculture can become more resilient and sustainable in the face of global challenges.

- **Enhanced Nutrient Availability**

  Role of Microbiome-Based Interventions: Probiotics for soil can include beneficial bacteria and fungi such as nitrogen-fixing bacteria and mycorrhizal fungi which enhances nutrient availability to plants [26].

  Impact: By promoting nutrient cycling and increasing nutrient bioavailability, these interventions can reduce the need for synthetic fertilizers and improve crop nutrient uptake [25].

- **Disease Suppression**

  Role of Microbiome-Based Interventions: Soil probiotics can include beneficial microorganisms that suppress plant pathogens, protecting crops from diseases [23].

  Impact: Reduced disease pressure leads to healthier crops, potentially decreasing the need for chemical pesticides and improving overall crop yield.

- **Soil Health and Structure**

  Role of Microbiome-Based Interventions: Soil probiotics can enhance soil structure and microbial diversity, contributing to improved soil health [29]

  Impact: Healthy soils with diverse microbial communities can better retain water and nutrients, reducing the need for excessive irrigation and fertilization [12].

- **Climate Resilience**

  Role of Microbiome-Based Interventions: Certain soil probiotics can enhance plant resilience to climate-related stresses, such as drought or extreme temperatures by improving water use efficiency and stress tolerance [24].

  Impact: These interventions can help maintain crop productivity even under changing climate conditions, reducing the risk of yield losses.

While the potential of microbiome-based interventions for agriculture is promising, it’s important to note that their effectiveness can vary based on factors like soil type, crop species and local environmental conditions [22]. Nonetheless, ongoing research in this field holds great promise for sustainable agriculture by reducing the environmental impact of chemical fertilizers, enhancing crop resilience and improving overall food security.

9 Challenges and Future Directions

Current Challenges in Studying and Manipulating Soil Microbiomes

Studying and manipulating soil microbiomes, although promising, presents several challenges. These challenges range from the complex and dynamic future of soil ecosystems to limitations in our understanding and technological capacities. Here are some current challenges in this field;

Microbial Diversity and Complexity Challenge: Soil ecosystems are incredibly diverse and complex, with an estimated one gram of soil containing thousands of microbial species. Characterizing and understanding this diversity is a significant challenge [1].

Lack of Cultivation Techniques challenge: Many soil microorganisms are difficult to culture in the laboratory, limiting our ability to study them directly and harness their potential for soil improvement [30].

Dynamic Nature of Soil Ecosystems Challenge: Soil microbiomes are highly dynamic and responsive to environmental changes. Studying their responses to various perturbations, including land-use changes and climate shifts, is challenging [31].

Data Integration and Analysis Challenge: Analyzing vast datasets generated from soil microbiome studies requires advanced computational tools and bioinformatics expertise. Integrating multiple data types, such as metagenomics and meta-transcriptomics is also complex [32].

10 Ethical and Regulatory Issues

The use of genetically modified microorganisms or soil probiotics in agriculture raises ethical and regulatory concerns regarding their potential ecological and health impacts [33].

Challenge of Scaling up Microbiome-Based Practices: Transitioning from small-scale microbiome research to large-scale agricultural application is challenging. Factors like scalability, cost effectiveness and compatibility with existing farming practices need to be addressed [34].

Addressing these challenges will require interdisciplinary efforts involving microbiologists, ecologists, agronomists and computational scientists. Despite the obstacles, understanding and manipulating soil microbiomes offer tremendous potential for sustainable agriculture, environment conservation and improved food security. Ongoing research and technological advancements continue to shed light on these complex ecosystems.

11 Emerging Research Areas and Technologies

Emerging research areas and technologies in the study of soil microbiomes are shaping the future of agriculture and ecosystem management. Two key areas are metagenomics and microbiome engineering, which offers powerful tools for understanding and manipulating soil microbial communities. Here’s an exploration of these areas;

Metagenomics

Definition: Metagenomics involves the study of genetic material directly extracted from environmental samples, without the need for isolating and cultivating individual microorganisms.

The role of metagenomics is that it allows researchers to analyze the entire genetic content of soil microbiomes, providing insights into microbial diversity, functional potential and metabolic pathways [32].

This technology has revolutionized our understanding of soil microbiomes, revealing the presence of numerous unculturable microorganisms and their roles in nutrient cycling, plant–microbe interactions and ecosystem functioning [1].

Microbiome Engineering

Definition: Microbiome engineering involves intentionally manipulating soil microbial communities to achieve desired outcomes such as improved crop yields, disease resistance or soil health.

The role of microbiome engineering: Researchers are exploring techniques to modify soil microbiomes by introducing beneficial microorganisms such as nitrogen-fixing bacteria or mycorrhizal fungi, to enhance nutrient cycling, suppress pathogens or promote plant growth [34].

Impact of Microbiome Engineering: This field holds the potential to revolutionize sustainable agriculture by reducing the need for chemical inputs, improving soil health and increasing crop resilience to environmental stresses.

Long-Read Sequencing Technologies

Emerging Technology: Recent advancements in long-read sequencing technologies such as Oxford Nanopore and PacBio, are enabling more accurate and complete sequencing of soil microbiome DNA. These technologies can help resolve complex microbial communities and their functional potential [35].

Impact: Long-read sequencing provides a deeper understanding of microbial genomes and metabolic capabilities, facilitating the identification of novel functions and interactions within soil ecosystems.

Advanced Data Analytics and Machine Learning

Emerging Technology: Advanced data analysis and machine learning approaches are being applied to large scale soil microbiome datasets. These techniques help uncover complex relationships between microbial communities, environmental variables and ecosystems processes [36]

Impact: Machine learning can predict soil microbiome responses to environmental changes and guide microbiome engineering efforts for tailored soil management practices.

These emerging research areas and technologies are advancing our knowledge of soil microbiomes and offering innovative solutions for sustainable agriculture, ecosystem restoration and environmental conservation. They hold the potential to transform how we manage soil ecosystems for a more resilient and food-secure future.

12 Conclusion

In the intricate web of life that supports terrestrial ecosystems, the soil microbiome emerges as a pivotal player, orchestrating the complex dance of nutrient conservation for the benefit of plant growth. The symbiotic relationships between plants and soil microorganisms have been sculpted by millions of years of coevolution resulting in an intricate partnership that facilitates nutrient cycling, enhances plant health and ultimately sustains life on earth.

As we've explored throughout this discussion, the soil microbiome contributes to nutrient conservation through various mechanisms. Nitrogen-fixing bacteria and mycorrhizal fungi unlock essential nutrients from the atmosphere and mineralize organic matter, ensuring a steady supply of nitrogen and other vital elements for plants. Organic matter decomposition enriches the soil with carbon, further enhancing nutrient retention and promoting plant health.

These mechanisms, driven by the myriad of microorganisms inhabiting the soil, collectively enhance nutrient availability for plants, offering a lifeline for growth and development. In return, plants provide carbon compounds and other resources to nourish their microbial partners. It's a delicate equilibrium, a dance of reciprocity, and it underscores the fundamental interdependence between plants and soil microorganisms.

The importance of this partnership extends beyond the boundaries of individual plants. It touches the heart of sustainable agriculture, as we seek to feed a growing global population while minimizing the environmental footprint of food production. Understanding and harnessing the soil microbiome hold the keys to achieving this delicate balance. Emerging research areas and technologies from metagenomics to microbiome engineering empower us to explore the hidden depths of soil microbial communities and unlock their potential for sustainable agriculture. We can now envision a future where precision agriculture, informed by soil microbiome insights, optimizes resource use, reduces chemical inputs and enhances crop resilience in the face of environmental challenges.

However, it is not without its challenges. The vast diversity and dynamic nature of soil microbiome, coupled with ethical and regulatory concerns, remind us of the complexity of this field. Yet, as we confront global challenges such as climate change, soil degradation and food security, the soil microbiome offers a glimmer of hope—a realm of opportunity to transform the way we interact with our planet's living skin.

In conclusion, the soil microbiome is not merely a silent observer but a dynamic partner in the grand tapestry of life. Its role in nutrient conservation for plant growth resonates far beyond the soil's surface, shaping our understanding of ecosystems, agriculture, and the future of a sustainable planet. As we continue to unravel its mysteries and harness its potential, we embark on a journey towards greener, more resilient and harmonious world where soil and plants thrive in a delicate symphony of life.

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Women Empowerment in Environmental Conservation

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Abstract The current global environmental landscape confronts unparalleled challenges, requiring a variety of perspectives to cultivate enduring solutions. This study delves into the crucial subject of promoting women's involvement in environmental preservation, aiming to rectify gender disparities in engagement. It explores the historical legacies of women in conservation, ranging from the pioneering work of Rachel Carson to the transformative Green Belt Movement led by Wangari Maathai. Employing a research approach deeply rooted in extensive secondary data, this study investigates the multifaceted aspect of women's participation in environmental preservation. The results spotlight significant historical and contemporary contributions, underlining the economic, social, and environmental advantages of empowering women. Recommendations underscore the necessity for gender diversity, inclusiveness, and skill enhancement within environmental organizations, policy development, and grassroots movements. A prominent discovery emphasizes the considerable impact women have in surmounting gender-related hurdles within the field, underscoring their resilience. This study offers actionable suggestions for promoting gender equality within the field, underscoring that women's empowerment in environmental preservation is a vital strategy for a sustainable future.

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However, this study highlights the pivotal role of women in addressing environmental challenges, providing insights into methods for fostering gender equality. It underscores the necessity for gender inclusivity in realizing global sustainability objectives, emphasizing women's contributions to environmental preservation as fundamental to shaping a more inclusive and sustainable future.

Keywords Women empowerment · Environmental conservation · Gender diversity · Sustainability · Conservation initiatives

1 Introduction

In an era defined by mounting environmental challenges, the urgency of adopting comprehensive and all-encompassing approaches to conservation cannot be overstated [1]. At the heart of these endeavors lies the indispensable role of women in the preservation of our environment. This chapter embarks on a journey to explore the empowerment of women in environmental conservation, emphasizing its critical role in shaping a sustainable future. Central to our investigation is the intricate interplay between gender and environmental conservation. This study delves into the historical and contemporary contributions of women to the field, addressing gender disparities while underscoring the transformative influence of women's active participation. The importance of women's engagement in environmental conservation goes beyond matters of social equity; it represents a strategic necessity in the face of escalating environmental crises. Women bring distinctive perspectives, knowledge, and leadership that are instrumental in cultivating a world resilient to environmental challenges. Furthermore, their active involvement holds the potential to enhance conservation efforts, making it imperative to recognize and harness this underutilized resource [2].

The development of this research has evolved from the recognition of women's historical, yet often overlooked, contributions to environmental conservation. This section draws from a comprehensive review of secondary data, encompassing seminal works in environmental literature, feminist studies, and reports from conservation organizations. Nevertheless, despite the richness of existing research, gaps persist in our understanding of the nuanced dynamics between women and environmental conservation. It is these voids that this chapter aims to shed light on, offering a foundation for a more equitable, resilient, and sustainable future for all. This chapter represents a multifaceted exploration that seeks to highlight the historical contributions of women to environmental conservation, taking inspiration from trailblazers such as Carson and Maathai [3]. It delves into the analysis of gender disparities and challenges within the field, informed by the research of scholars like [4, 5]. Moreover, it endeavors to unveil the extensive economic, social, and environmental benefits resulting from the empowerment of women in environmental protection, firmly grounded in research such as that of Agarwal [6]. In addition to providing valuable insights, this chapter offers practical recommendations aimed at fostering gender diversity within conservation organizations, drawing from research by esteemed

Table 1 Historical figures in environmental conservation

Name	Contributions	Period
Rachel Carson	Silent Spring author, pioneer of environmentalism	1907–1964
Wangari Maathai	Green Belt Movement founder, tree planting	1940–2011
Marjory Stoneman Douglas	Advocacy for Everglades preservation	1890–1998
Chico Mendes	Advocate for Amazon rainforest preservation	1944–1988
Sylvia Earle	Marine biologist, ocean conservation	1935-present

organizations like The Nature Conservancy [7]. Furthermore, it underscores the pivotal role of education and capacity building as transformative tools for empowering women in the domain of environmental conservation, drawing inspiration from programs such as Women for Nature initiated by Nature Canada in 2021 [8].

2 Historical Perspective

2.1 The Historical Contributions of Women to Environmental Conservation

The historical impact of women on environmental conservation, though often underappreciated, has been immensely influential. A prime illustration is Rachel Carson, whose groundbreaking work, "Silent Spring" (1962), is prominently featured in Table 1. This masterpiece drew attention to the catastrophic effects of pesticides and ignited the modern environmental movement. Carson's research laid the foundation for environmental activism, representing a turning point in our comprehension of humanity's influence on the environment [9]. Likewise, Table 1 spotlights Wangari Maathai, the visionary founder of the Green Belt Movement in Kenya, who made substantial contributions to reforestation and community empowerment [10]. Her endeavors epitomize grassroots-driven environmental conservation led by women, leaving an enduring legacy in sustainability.

2.2 Early Examples of Women in Environmental Activism

Early examples of women's involvement in environmental activism extend beyond the well-known figures. Women played vital roles in the conservation movement during the late 19th and early twentieth centuries. Notable among them is Mabel Osgood Wright, a proponent of bird conservation in the United States who authored books promoting bird-friendly landscaping. Her work, such as "Birdcraft" (1897), contributed to growing awareness of the need to protect bird species and their habitats

[11]. Women like Rosalie Edge, who established the world's first hawk sanctuary in 1934, played a pivotal role in safeguarding raptors and their environments [12].

2.3 Key Figures and Their Impact

The lasting impact of key women figures on environmental conservation remains indelible. Ellen Swallow Richards, a pioneer in the home economics and environmental science movement, conducted pioneering studies on water quality and sanitation, laying the groundwork for greater environmental consciousness and public health improvements [13]. Marjory Stoneman Douglas, celebrated for her influential work in safeguarding the Florida Everglades, significantly heightened public awareness of wetland conservation. Her magnum opus, "The Everglades: River of Grass" (1947), played a pivotal role in advocating for the preservation of this unique ecosystem [14]. These women, among many others, have made substantial contributions to the environmental conservation movement, enriching our understanding of environmental issues and actively shaping strategies and policies for environmental safeguarding.

3 Gender and the Environment

3.1 Understanding the Gender-Environment Nexus

A profound understanding of the intricate connection between gender and the environment is essential for comprehending how gender dynamics influence environmental challenges and solutions. Scholars like [15] have highlighted the complex interplay between gender, the environment, and sustainable development. This comprehension extends to recognizing that environmental issues often impact women and men differently due to their distinct roles and responsibilities within society. This section delves into how gender norms, roles, and identities influence individuals' interactions with the environment, encompassing aspects ranging from resource utilization to environmental decision-making processes.

3.2 Gender Disparities in Access to and Control Over Environmental Resources

The issue of gender disparities in access to and control over environmental resources is of paramount concern. Bina Agarwal's work in "Gender and Green Governance" sheds light on how women, particularly in rural contexts, may encounter restricted access to land, water, and forests, thus limiting their participation in and benefits from environmental conservation and resource management [6]. Understanding these discrepancies is necessary for effectively tackling environmental challenges and nurturing reasonable solutions.

3.3 The Role of Gender in Sustainable Development

The pivotal role of gender in sustainable development cannot be overstated. Scholars like [16] have delved into the significance of integrating gender perspectives into sustainable development strategies. This section explores how gender equality constitutes a fundamental element in achieving sustainability goals, as recognized in the United Nations Sustainable Development Goals (SDGs). Gender considerations permeate various SDGs, encompassing poverty alleviation, education, clean water, and sanitation, thus underscoring the interconnectedness of gender and environmental sustainability. Grasping the gender-environment relationship, acknowledging gender disparities in resource access, and appreciating the significance of gender in sustainable development are all pivotal in crafting comprehensive and effective approaches to environmental preservation and sustainability. These insights not only inform policy and practice but also underscore the imperative of achieving gender equality in the pursuit of global environmental goals.

The gender environment nexus significantly shapes international agreements by emphasizing gender dynamics, recognizing gender-specific impacts in resource conflicts, supporting cross-border collaboration, addressing domestic resource inequalities, promoting gender-inclusive urban planning and education, and ensuring women's participation in environmental decision-making at all levels as shown in Fig. 1.

4 Challenges Faced by Women in Environmental Conservation

4.1 Discussing the Barriers and Obstacles Women Encounter

The barriers and obstacles women encounter in the field of environmental conservation are multifaceted and deeply ingrained in societal structures. Studies by scholars like [15] have delved into the concept of intersectionality, emphasizing that gender is just one aspect of a person's identity, and factors like race, class, and ethnicity also play a critical role in shaping the challenges individuals face in environmental conservation. Common barriers include limited access to education and training, restricted mobility in rural areas, and a lack of representation in decision-making roles. Numerous obstacles obstruct the full participation of women in environmental

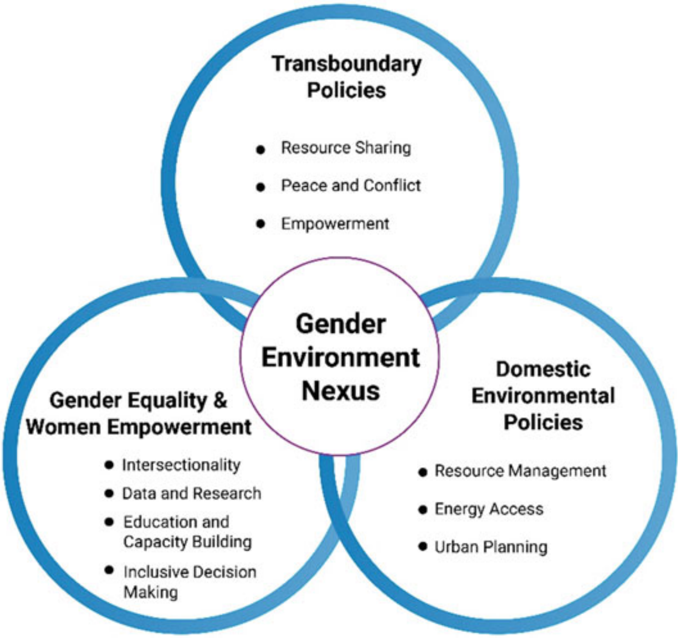

Fig. 1 Gender environment nexus

initiatives. Women engaged in environmental conservation confront a multitude of challenges, foremost among them being deeply ingrained gender disparities that curtail their access to resources and decision-making roles. These challenges often encompass the burdens of unpaid caregiving responsibilities, concerns for personal safety, and the threat of violence in remote areas, all of which act as deterrents to their active involvement. Inadequate access to education and training, resource conflicts, financial support limitations, cultural norms, and a dearth of networking opportunities further impede their engagement. The demanding nature of conservation work can have adverse effects on women's health and well-being, particularly in the absence of support systems. Mobility restrictions in certain regions compound these obstacles, underscoring the multifaceted nature of the challenges women face in their conservation endeavors, as depicted in Fig. 2.

4.2 Gender-Based Discrimination in the Environmental Field

Persistent and extensively documented, gender discrimination remains an enduring problem within the environmental sector. As outlined in Lund et al. [17]'s study, gender biases are prevalent and often result in the exclusion of women from involvement in environmental planning and resource management. This discrimination

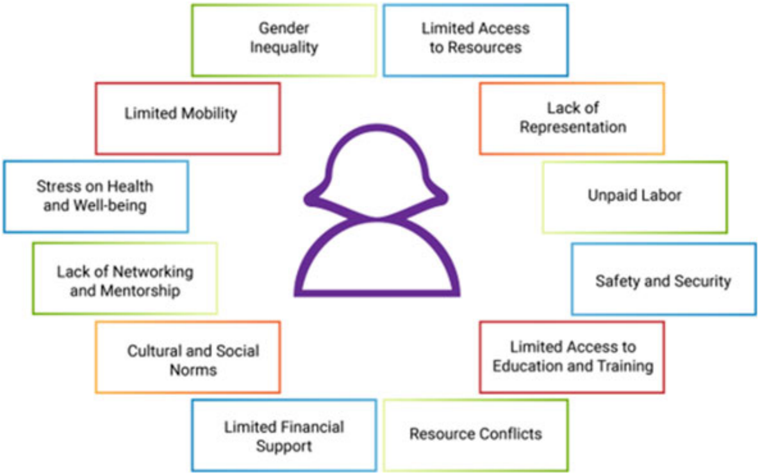

Fig. 2 Challenges faced by women in environmental conservation

manifests in various ways, such as unequal compensation, restricted career advancement opportunities, and a failure to acknowledge women's accomplishments. Recognizing and comprehending these discriminatory practices is imperative to eliminate them and foster inclusivity within the environmental industry.

4.3 Case Studies Illustrating Challenges and Potential Solutions

This section includes case studies from divergent regions and circumstances to give real insights into the issues faced by women in environmental conservation and potential solutions. For example, the United Nations (2017) study "Women in the Changing World of Work: Planet 50–50 by 2030" provides a worldwide viewpoint on the challenges women face in environmental conservation [18]. Case studies from non-governmental organizations (NGOs) such as the World Wildlife Fund (WWF) and Conservation International highlight activities targeted at tackling these issues [19]. These activities frequently include training and education, assistance for women-led ventures, and campaigning for gender-responsive policy.

Exploring the problems and hardships experienced by women in environmental conservation, putting attention on gender-based discrimination, and presenting case studies that reflect real-world challenges and potential solutions are all important steps toward fostering gender equality in the environmental sector. These insights not only expose the difficulties that women confront but also provide solutions to these difficulties, creating a more inclusive and successful approach to environmental protection.

5 Benefits of Women's Empowerment in Environmental Conservation

5.1 Exploring the Positive Impacts of Women's Involvement

Understanding the multifaceted contributions that women make in environmental conservation is dynamic. Esteemed scholars such as Agarwal [20] have conducted extensive research in this domain, emphasizing that women' participation often results in more sustainable and equitable resource management. Their involvement spans from small-scale sustainable farming practices to community-led conservation efforts, frequently leading to innovative solutions that benefit both local communities and the environment [21]. This section delves into how women's distinct perspectives and experiences enrich and enhance the effectiveness of conservation strategies. Empowering women in environmental conservation is essential for fostering diverse and sustainable solutions. They lead community-based initiatives, promote sustainable practices, preserve biodiversity through traditional knowledge, enhance climate resilience, and elevate environmental awareness, all while driving economic opportunities and innovation for a more inclusive and sustainable future.

5.2 Economic, Social, and Environmental Benefits

The economic, social, and environmental benefits stemming from the empowerment of women in environmental protection are substantial. Women's active involvement in conservation can lead to increased household income, improved nutrition, and enhanced livelihoods. Furthermore, women's roles in natural resource management, such as reforestation and sustainable agriculture, contribute to environmental sustainability and ecosystem restoration. Research by Rosche [21] has demonstrated that women's participation in agriculture has the potential to increase food security and reduce environmental degradation.

6 Highlighting Successful Projects and Initiatives

Highlighting successful projects and initiatives where women have played a central role showcases the real-world impact of their involvement. One notable example is the Green Belt Movement in Kenya, founded by Wangari Maathai, which has empowered thousands of women to plant trees, combat deforestation, and improve local ecosystems [24]. Another success story is the Chipko movement in India, where women embraced tree-hugging as a form of protest to protect their forests [23]. These initiatives not only yield environmental benefits but also demonstrate the leadership and resilience of women in the face of environmental challenges.

Fig. 3 Empowering women for inclusive and sustainable environmental conservation

Exploring the positive impacts of women's involvement, understanding the economic, social, and environmental benefits, and highlighting successful projects and initiatives led by women are essential for recognizing the significant contributions they make to environmental conservation. These insights not only underscore the value of women's empowerment but also provide inspiration and models for broader gender-inclusive environmental initiatives Fig. 3.

7 Women's Participation in Conservation Organizations

7.1 Analyzing the Representation of Women in Conservation Organizations

Evaluating women's presence in conservation organizations is critical for assessing gender diversity and inclusiveness in the industry. Berkes et al. [24] conducted a study on the gender composition of conservation organizations, which revealed discrepancies in representation. This section investigates the degrees of women's engagement at various levels, ranging from entry-level jobs to leadership roles, as well as the reasons that contribute to women's underrepresentation in specific organizations.

7.2 Leadership Roles and Decision-Making Positions

The participation of women in leadership and decision-making roles within conservation organizations is heavily weighted. Westley and Vredenburg [25] research on women's roles in environmental governance emphasizes the revolutionary potential of female decision-making leadership. This section explores the challenges and prospects of women running for leadership positions and the implications of women's leadership toward conservation organization's direction and goals.

7.3 Efforts to Promote Gender Diversity in Environmental Organizations

Environmental organizations have recently embraced gender diversity initiatives. Many organizations and projects such as "Women in Nature" by the Nature Conservancy have been instituted in efforts towards addressing gender inequities and creating a conducive environment. Some researchers such as Enarson [26] examined their effectiveness in promoting gender equity. The current part discusses ways through which organizations enhance gender diversity such as mentorship programs, sensitive policies on gender, and campaigns targeting girl children and women seeking employment in environment stewardship. However, analyzing the representation of women in conservation organizations, exploring their leadership roles, and discussing efforts to promote gender diversity is essential for recognizing the progress made in the environmental sector and identifying areas that require further attention. These insights not only highlight the importance of gender inclusivity in the field but also provide valuable lessons for enhancing the role of women in conservation organizations.

8 Capacity Building and Education

8.1 The Role of Education and Training in Empowering Women in Environmental Conservation

The role of education and training in empowering women in environmental conservation is a fundamental component of achieving gender equality in the field. Scholars like Agarwal [27] have emphasized the significance of education in equipping women

Table 2 Training programs for women in conservation

Program name	Initiating organization	Program description
Women for nature	Nature Canada	Capacity building for women in conservation
Green women leaders	Environmental NGO	Leadership and skills development
EmpowerHER conservation	International initiative	Empowering women in conservation efforts

with the knowledge and skills needed to participate actively in environmental initiatives. Capacity building for women in environmental conservation involves four key elements education and training as shown in Fig. 3 for understanding environmental issues and sustainable practices, ensuring resource access and responsible management, developing leadership and advocacy skills to take on key roles and advocate for policy changes, and fostering networking and collaboration to connect with others, share experiences, and access resources and partnerships, all of which enhance their impact in the field. This section delves into how education broadens women's understanding of environmental issues, enabling them to engage in sustainable practices and conservation efforts effectively.

8.2 Showcasing Training Programs and Initiatives

Showcasing training programs and initiatives that focus on women's empowerment in environmental conservation, as illustrated in Table 2, provides concrete examples of capacity-building efforts. The UNEP (United Nations Environment Programme) has launched initiatives like the "Empower Women" program, which offers training and capacity-building opportunities for women in environmental fields 30. This section highlights the structure, objectives, and achievements of such programs, underscoring how they provide women with the necessary skills and knowledge to excel in environmental conservation.

8.3 Success Stories of Women Who Have Benefited from Capacity Building

Sharing inspiring stories of women who have benefited from capacity-building programs and education demonstrates the transforming impact of these efforts. Women like Vandana Shiva, an environmental activist and eco-feminist, serve as examples of how education and training may equip women to take on leadership roles in environmental conservation [28]. This section features personal stories and

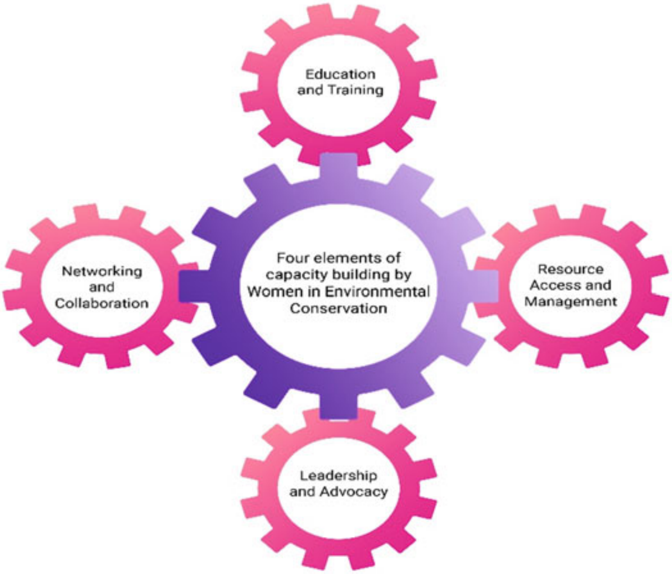

Fig. 4 Enhancing women's capacity for sustainable impact in environmental conservation

accomplishments that highlight how capacity development has helped women break down barriers and make important contributions to the profession.

Education and training are critical for empowering women in environmental conservation and providing women with the tools they need to effect long-term change [29, 30]. Displaying training programs and sharing success stories demonstrate the good impact of these efforts, motivating and encouraging more women to seek jobs in environmental conservation Fig. 4.

9 Community Involvement and Grassroots Movements

9.1 The Impact of Women-Led Grassroots Movements on Environmental Conservation

Women-led grassroots movements play a profound role in environmental conservation and have been a focal point of various scholarly investigations. Vandana Shiva's ecofeminist research underscores the pivotal significance of women at the helm of grassroots movements, particularly in developing nations [31]. These movements frequently tackle pressing issues such as deforestation, water resource management, and sustainable agriculture. This section delves into the amplification of women's roles in advocating for environmental conservation within grassroots movements and their contributions to both social and environmental justice.

9.2 Case Studies of Women-Led Community Projects

Case studies spotlighting women-led community initiatives provide tangible evidence of the transformative power of local endeavors. The Chipko movement in India, where women embraced trees to safeguard their forests, stands as an exemplary illustration of grassroots action [26]. Similarly, the Barefoot College in India, founded by Bunker Roy, empowers rural women through solar engineering and water management programs [32]. These case studies underscore the vital role of women in instigating and guiding conservation efforts at the community level.

9.3 The Importance of Local Knowledge and Women's Leadership

The unification of local knowledge and women's leadership in environmental conservation stands as a critical theme explored by scholars such as [22, 23]. Local knowledge often finds its roots in age-old practices and constitutes a valuable resource for sustainable environmental management. Women's leadership within communities ensures the preservation and integration of this wisdom into conservation endeavors. This section discusses the significance of uniting women's leadership and local knowledge to effectively address environmental challenges. Women-led grassroots movements undeniably wield substantial influence on environmental conservation, frequently yielding tangible results at the community level. Case studies serve as exemplars of successful initiatives, while the significance of local wisdom and women's leadership underscores the vital role women play in conserving traditional practices and propelling sustainable environmental solutions.

10 Policy and Advocacy

10.1 Women's Role in Advocating for Environmental Policies

The involvement of women in advocating for environmental policies has gained recognition and significance in recent years. Scholars like Moser [33] have delved into the active participation of women in advocating for environmental preservation. Women frequently organize advocacy groups, engage in environmental activism, and lobby for policies that address issues such as climate change, natural resource management, and sustainable agriculture. This section explores the multifaceted ways in which women contribute to shaping environmental policies through their advocacy endeavors.

10.2 Legislation and Policy Changes Driven by Women

Women's policy shifts have resulted in substantial changes in environmental governance. In the UK, for example, the Women's Environmental Network (WEN) has played an important role in implementing legislative reforms for waste handling and hazardous chemicals [34]. The Uganda Women's Climate Center has also called for gender-specific climate policies [35]. This shows the legislative and political development of the women's lobby, which focused on its environmental activities.

10.3 Challenges and Successes in Promoting Gender-Inclusive Policies

Promotion of gender-inclusive policies is not an easy job; it has been achieved, but there have also been failures. Otzelberger [36] examined the challenges of environmental policy responsiveness to women's needs. This part is about barriers that women face during their efforts to push for gender-responsive policies including, fighting prejudices and few numbers in decision-making positions. Also, it contains success stories and the best approaches for generating and applying policies based on women's peculiar needs and commitments to nature protection. However, women's advocacy for environmental policies has made a huge contribution towards the development of gender-friendly environmental governance. The concrete effects of this work manifest in examples of legislation and policy reforms initiated by women. However, achievements towards gender-sensitive policies confirm that women's voices matter in making the environmental policy space.

11 Women in Science and Research

11.1 The Contributions of Women Scientists and Researchers in Environmental Fields

Some important aspects of women's involvement in environmental problems. For instance, Breton [37] has stated that women were at the forefront of various fields including environmental science and engineering. Sylvia Earle—one of those marine scientists dealing with oceans. Therefore, women's participation in Ecology, Climate

Science, and Conservation Biology has created a clear view of environmental problems [38]. This section discusses how various women scientists played an important role in environmental awareness and conservational activities.

11.2 Barriers and Breakthroughs in STEM (Science, Technology, Engineering, and Mathematics)

Understanding the difficulties and achievements regarding STEM (Science, Technology, Engineering, and Mathematics) disciplines helps one realize the problems facing women in scientific research. A scholar [39] has highlighted the issue of gender disparities in its roles in STEM and has pointed out the obstacles to women's success including biases, lack of resources, and lack of equality. The challenges experienced by women in STEM and some examples of success stories regarding the improved inclusion of women in scientific research are discussed in this section.

11.3 Advancements in Gender Equality in Scientific Research

The cooperation of some women scientists, policy-makers, and organizations has helped in advancing this cause. UN initiatives towards gender equality in science, technology, and innovation. L'Oreal's "For Women in Science" and UNESCO's "For Women in Science", are some initiatives that acknowledged and promoted female scientists' achievements and positions of leadership [40]. In this section, the development towards an equal representation of men and women in science is also discussed with relevance to environmental science and conservation. Environmental understandings and conservations would not be what they are today without the scientific and research works of women. While they have encountered challenges in STEM-related fields, significant discoveries and advances in gender equality have revolutionized the landscape of scientific study, ensuring that women's opinions are heard and appreciated in the field of environmentalism.

12 Case Studies

12.1 Showcasing Notable Women in Environmental Conservation

Case studies that bring attention to the remarkable women who have made substantial contributions to environmental conservation, as illustrated in Table 3, are of immense value in showcasing the diverse and impactful roles women assume in

Table 3 Case Studies of Women in Environmental Conservation

Name	Achievements	Geographic location
Jane Goodall	Research and conservation efforts with primates	Africa
Berta Cáceres	Advocacy for Indigenous and environmental rights	Honduras
Gro Harlem Brundtland	Sustainable development advocacy	Norway
Marina Silva	Amazon rainforest preservation and governance	Brazil
Isatou Ceesay	Waste management and women's empowerment	Gambia

this field. Wangari Maathai's case, the founder of Kenya's Green Belt Movement, stands out prominently, as depicted in Table 3 [10]. Her efforts in tree planting, environmental education, and women's empowerment resulted in reforestation and sustainable development. Another compelling case is that of Parameswaran, an Indian environmental activist, and eco-feminist, celebrated for her advocacy of biodiversity and sustainable agriculture [41], as shown in Table 3. These case studies vividly demonstrate the capacity of individual women to instigate transformative change in environmental conservation.

12.2 Diverse Examples from Around the World

To portray accurately the significant role women have played in safeguarding the environment, it is imperative to encompass diverse examples from around the world. For instance, in the United States, Rachel Carson's pioneering study on the ecological ramifications of pesticides, as documented in her seminal work "Silent Spring" (1962), culminated in the prohibition of DDT and catalyzed the contemporary environmental movement. Meanwhile, Marina Silva, a former Minister of the Environment in Brazil, played a pivotal role in establishing protected areas and advocating for sustainable development in the Amazon rainforest. Isatou Ceesay initiated the Women's Initiative in The Gambia, focusing on waste management, ecological sustainability, and women's economic empowerment [42]. These diverse case studies unequivocally underscore the worldwide scale of women's involvement in environmental conservation. These chronicles of leadership, inventiveness, and influence draw inspiration from women who have made remarkable contributions to environmental conservation. Such examples from across the world vividly depict the critical role that women play in addressing environmental problems and improving sustainable practices.

13 Future Prospects and Recommendations

13.1 Envisioning the Future of Women's Involvement in Environmental Conservation

Envisioning the future of women's environmental conservation participation is critical for constructing a more inclusive and sustainable world. Scholars such as Chaurasiya and Gadgala [43] have emphasized the need for women to play important roles in tackling environmental issues. More women should be in positions of leadership, decision-making, and research in the future. This section explores the prospective contributions of women to environmental protection in the coming years.

13.2 Recommendations for Empowering More Women in the Field

More women participating in environmental conservation are critical for ensuring gender equality and sustainability. Scholarship and mentorship programs, as well as the establishment of gender-sensitive legislation and the support of women-led projects, are all significant. The Nature Conservancy's (2020) study on gender diversity in conservation offers practical recommendations, including targeted recruitment, leadership development, and the enhancement of organizational culture [5]. This section elaborates on these principles and underscores their significance in enhancing women's involvement in environmental conservation.

13.3 The Potential Impact of Gender Diversity on Environmental Conservation

Gender diversity possesses the potential to exert a substantial influence on environmental preservation. As per the research findings of [44], gender-inclusive strategies often yield more effective resource management and sustainable practices. Gender diversity can usher in fresh perspectives, greater community involvement, and improved decision-making [45]. This section explores how a more diversified and gender-inclusive environmental sector could adeptly address intricate environmental challenges while contributing to the attainment of global sustainability objectives.

In contemplating the future of women's involvement in environmental conservation, offering recommendations to fortify their presence in the field, and acknowledging the potential influence of gender diversity, we embark on crucial strides toward attaining gender equality and enhancing environmental sustainability. These discoveries pave the way for a more comprehensive and triumphant approach to environmental conservation.

14 Conclusion

This study diligently studied women's crucial role in environmental conservation, shedding light on their historical contributions, gender inequities, and the multidimensional economic, social, and environmental benefits of women's empowerment in this sector. We investigated women's active engagement in conservation organizations, highlighted the important necessity for capacity building and education, investigated their crucial roles in grassroots movements, and pushed for gender-inclusive legislation. Furthermore, we've highlighted individual case studies of women who have made an everlasting effect on environmental protection throughout the world. The knowledge gained from this chapter underlines the undeniable potential of women in tackling environmental concerns and advancing sustainable practices. History has seen women being persistent in surpassing gender biases. They have also greatly contributed to the conservancy. The current chapter focused on gender issues such as increased gender diversity and inclusion in environmental institutions, policymaking, and grassroots work. It stressed the importance of capacity building and education in empowering women to conserve the environment. Women's empowerment in the conservation of the environment transcends the equality of genders and its necessity for a sustainable environment. They can inspire immense change due to their different points of view, experience, and steadfast commitment to environmental conservation. The case studies in this study suggest that women can be a force for change concerning environmental challenges and promote sustainable practices. The focus of this chapter is on empowering women for their role in protecting the environment. It fosters an equal rights and multi-gender strategy toward achieving sustainability at the global level by recognizing the significant part that women play in the achievement of sustainability at the global level.

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Future Direction of Environmental Conservation and Soil Regeneration

Katherine Georgina Menon, Venkateswar Reddy Kondakindi, Ranjit Pabbati, and P. Paul Vijay

Abstract The well-being of the Earth's ecosystems is intimately correlated with the condition of its soils, environmental preservation and soil regeneration are essential to preserving the long-term viability of the planet. The foundation of terrestrial life is soil, which supplies vital nutrients, fosters plant growth, controls water cycles, and acts as a carbon sink. The urgent need for environmental conservation and soil regeneration has come to light in light of current fast industrialization, urbanization, and unsustainable land management practices. This chapter examines the significance of environmental preservation in the context of soil regeneration, examining various approaches, their advantages, and the difficulties involved in carrying out these vital tasks.

Keywords Environment · Conservation · Soil · Pollution

1 Introduction

Soil is an important element of our earth that supports various biomes, because it supports crucial social and ecosystem services, The Soil system is intricate at the interface of the atmosphere, lithosphere, hydrosphere, and biosphere that is essential to food production and essential to sustainability [5, 10].

Soil is made up of inorganic and organic particles that are organized in a three-dimensional framework with spaces filled with air and water in between the particles. Due to its composition, soil life can survive in the voids, where it has a place to physically conceal from predation and unfavorable above-ground circumstances while

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still obtaining water, nutrients, and oxygen. In terrestrial systems, the diversity of life is greater below ground than above ground [3, 18]

Annual increases in global population raise questions about energy usage and its effects on the environment. According to current publications, resources like natural gas, coal, and oil account for 80% of all energy usage. Additionally, the exploitation of these limited resources causes serious environmental issues such water pollution, rising temperatures, and air pollution [2, 98]. These factors influence the quality of our environment, where the key concern in the present moment is soil health. The phrase "soil health" has its historical roots in the term "soil quality," which refers to a soil's ability to support agriculture and its near environment. As a result, the quality of the soil also affects the health of the plants, animals, and entire ecosystems [20].

The world's arid and semi-arid regions are severely constrained in their ability to produce crops sustainably due to little moisture, short growing seasons, extremely unpredictable meteorological conditions, pests, and single planting patterns [45]. The notion of sustainability in agriculture emerged around the 1980s as a result of the growing recognition of global environmental degradation. It then made its way onto the agendas of major entities such as the United Nations. The Brundtland Report defined sustainable development as "meeting the requirements of the present without jeopardising future generation's potential" [13].

Pre-harvest losses from arthropod pests of crops grain range from 15 to 100% in developing nations, where population expansion is most likely to outpace grains in yields, and post-harvest losses from 10 to 60% [48]. For thousands of years, people have used pesticides to try and manage insect infestations. The Romans and other ancient civilizations noted the use of substances like sulfur as well as heavy metals and salts in agriculture. The first generation of insecticides contained extremely dangerous substances, such as "Paris green," a copper acetoarsennite that was widely used in the United States between 1867 and 1900 and contained arsenic [31]. Concerns regarding pesticide influence on the ecosystem, farmworkers and customer's health and other issues developed soon after they were introduced**.** Recent developments in biotechnology and computational technology have made it possible to replace synthetic materials and made use of Genetically modified plants with several options. These methods claim to deliver more enduring and long-lasting solutions.

In order to overcome the side effects caused by the use of harmful pesticides and chemical fertilizers, the use of biopesticides and biofertilizers had begun. Biofertilizers are single or multiple strains of microbes such as algae, bacteria, and fungus that improve plant growth by colonising the rhizosphere and the inside of the plant and by increasing nutrient availability that can be supplied to the seeds, plant surface, or soil [60]. As a result, the biofertilizer industry is predicted to grow from 2.3 billion USD in 2020 to 3.9 billion USD in 2025. Biofertilizers are well-known for their capacity to deliver nutrients to plants such as nitrogen, phosphate, zinc, and phosphorus while also boosting plant development [91].

On the other hand, the significance of ecology and its functioning is increasingly articulated through the paradigm of natural ecosystems: that ecosystems provide essential life-enhancing functions to humans. Year after year, unusual and severe weather events are reported all around the world. In 2021. The extent of the devastation was severe in Germany and Belgium, resulting in multiple deaths. Tropical cyclones have become more powerful in Asia in recent years. Furthermore, Japan has experienced more heavy rain, flooding, and landslides than ever before [63]. The drastic change in the environment has led to plant stress conditions [80].

Environmental factors such as local geo-climatic and seasonal variations, external circumstances of temperature, light, humidity, and physiological changes, among others, can cause changes in biomass output and secondary metabolite biosynthesis in plants [6].

2 Reasons for Soil Deterioration

Degradation or degradation of soil actually means loss of most important crops and soil fertility due to factors such as the environment or human activities. As mentioned, soil formation and degradation are both considered a natural process. For example, erosion is a process that does not stop until the land, including hills and mountains, is flattened. Even without human intervention, soil materials are removed from the surface of the earth by water, wind and gravity. In addition to many changes in the physical environment such as sea level rise, drought and global warming, global processes such as landscape development, volcanic activity and natural soil seepage can also be the main cause of degradation. Additionally, natural disasters such as floods, hurricanes, earthquakes, and deforestation can accelerate or cause soil degradation. The "accelerated degradation" of soil, called anthropogenic, occurs faster than the aging process. Many human activities can cause land degradation, including overuse and abuse of land resources [33]. In this section, let's discuss and understand some of the reasons for soil deterioration or deterioration.

2.1 Deforestation and Overgrazing by Cattle

Due to deforestation and overgrazing by cattle, the soil loses nutrients required for vegetative growth and the soil becomes infertile in terms of biodiversity. According to **("Problems of Livestock Population" by Sahay, K.B)**, removal beyond legal limits, oil and mineral extraction, farming for forest land, fire hunting and overgrazing are causing loss of vegetation on the land and other challenges. 467 million cows graze on 11 Mha of pasture; The average of 42 cows per hectare is higher than the sustainable population of 5 animals per hectare [76]. Animal pressure in arid regions leads to overgrazing, which reduces seepage while accelerating runoff and soil erosion. Overgrazing causes above-ground soil loss at meso and macro scales [37]. The rapid growth in commercialization of land and forests has caused great stress and depletion of soil nutrients, elements and microbial ecosystems that play a role in maintaining and regenerating the health of soil to support vital livelihoods.

Removing trees or plants, especially in or around a body of water, will wash away nutrient sediments from the soil [92].

2.2 *Urbanization*

It is the settlement of people in concentrated areas. area. The effect is negative. The reasons include serious air pollution, improper disposal of hazardous waste, deforestation, excessive drainage, e-waste, etc. it could be. Increasingly, urban conditions are being discovered to be more destructive. In this sense, scale corresponds to the geographical area or time of the process. The term "local scale" refers to certain actions or initiatives at the individual, group, or global level, such as the environmental impact of indoor air that may be most easily noticed and evaluated. Although data on indoor air pollution can be collected worldwide, human health concerns rarely arise in understanding the processes that produce these air pollutants, their unequal distribution, and how they affect the region or the world. In contrast, the environmental impact of CO_2 emissions is often described as a global issue [47]. The effects of mining include water scarcity due to falling water levels, soil pollution, partial or complete extinction of plants and animals, air and water pollution, and acid mine problems. Removal of overburden from the mining site leads to serious destruction of vegetation and valuable nutrients [77]. According to McGranahan et al., the change in impact is associated with urban expansion and economic growth. In other words, as cities progress, one environmental problem turns into another (with its consequences). This theory, known as "urban transformation", examines the types of environments and forms of management that exist in cities with different income levels, time, space, etc. It is useful because it can be used to detect how it changes according to changes. to change. and their type. The theory suggests three main dimensions of analysis: local, citywide, and global [50].

2.3 *Climate Change*

Climate; It refers to the general or environmental climate in a region, including long-term variations in wind, precipitation, and temperature. The rate at which the makeup and purpose of soil microbial communities are changing which is directly and indirectly affected by climate change. Given body temperature and changes in temperature and rapid population growth in the community, changes in the environment will affect the relative number of diseases in the community, soil and their functions [14, 99]. It has been well documented how changes in climate directly affect microbial makeup, population, and function [9, 15]. Water and temperature are important environmental factors that control microbial growth. As temperature rises, microbial communities adapt to support processes including respiration, fermentation, and methanogenesis. The body's systems as well as the enzymatic activity of bacteria are directly impacted by this effect. Climate change and agricultural issues both have an impact on the entire world. Through direct changes in the chemical and physical environment of soil and changes in land use, climate change affects microbial community structure and function. It is worth noting that the global warming feature of temperature increase has a straight effect on the microbial soil respiration rate, as soil microorganisms and other activities are sensitive to temperature. In recent years, many studies have focused on how climate change, especially temperature, affects microbial metabolism Chen [11, 24, 29, 39]. This demonstrates the significant impact of climate change on soil organisms, which are an important part of ecosystems & are important for sustaining soil health through ecological use. Forest fires also cause soil erosion as they destroy vegetation and trees on the ground.

2.4 Erosion

The process of removing soil, rock or crust by dissolving material from one region of the earth and then transporting it to another region to be deposited is called the process of erosion. “erosion” according to (the editors of Encyclopedia Britannica), there are 3 types of erosion as follows [22]:

(A) ***Water Erosion:*** Detachment, transport, and deposition are three methods associated with water erosion. An important first step in our understanding of erosion is the recognition of the important role that rainfall impacts play in soil erosion. Early theories were not considered variable as a source of isolation [12]. In protected tillage systems, the kinetic energy of raindrops is distributed by plant residues between living plants and dead plants, preventing decomposition. Rapid water erosion causes three different sorts of damage to farmland: loss of organic matter, a drop in the amount of nutrients that are accessible, and a shift in the water table. Despite extensive research on these effects and many local issues such as subsoil acidity, fragipans, and short bedrock depth [41], Some quantitative models for soil have not been created, according to [94]. Due to the interaction of pre-existing variables, it is challenging to forecast how soil loss & displacement through erosion would affect crop yields. Such as soil quality, topography, climate, crop genetics, and agricultural development [35].

(B) ***Wind erosion:*** It is the movement and settling of soil by wind. It is more prevalent in arid and semi-arid environments, yet this is untrue. Loss of vegetation due to excessive grazing or agriculture is one of the main reasons for this [88].

(C) ***Glacier Erosion:*** Glacier erosion occurs in two main ways: by the removal of rocks from the glacier bed, and by the destruction of surface materials by the (usually abrasive) grinding of ice into the ground. Cause of wastage of ice at its base). The eroded material moves until it is released or the glaciers melt [22].

2.5 Chemical Degradation

Chemical soil degradation is the term for unfavourable changes in soil chemistry that result in a reduction in soil quality as a byproduct of human endeavour. Chemical soil pollution accounts for around 12% of the total area affected by human-induced soil deterioration. About 12% of the degraded soils in Africa, Asia, Central America, and Europe are chemically impacted. Chemical deterioration is responsible for about 30% of the degraded soils in South America [61]. The main causes of chemical soil degradation are poor farming practices and deforestation. According to Thomas Francis Shaxson [94] "anthropogenic soil nutrient depletion" refers to the loss of nutrients due to faster processes and the reduction in soil nutrients caused by the addition of nutrients to agricultural products without any change in nutrients. Leaching and soil erosion. Even in natural vegetation, leakage occurs, but agricultural operations can have a considerable negative influence [30]. Nutrient leaching is common in soils with high water permeability and poor nutrients, such as sandy soils and fine iron soils with low clay reactivity and low organic matter (Oxisols, Ultisols) [75]. Most of the nutrients leached from the soil are: nitrate, sulfate, calcium, potassium and magnesium [30, 65, 75]. Another way soil chemically degrades is through acidification. Acidification may occur at high altitudes and in severe weather conditions due to the release of mixed acids in soils composed of acidic parent materials, in regions with high rainfall, due to long-term alkali leakage, and erosion. It will last longer because iron and aluminum oxides predominate. However, agriculture has the ability to hasten or even start soil acidification. Agricultural soil acidification is caused by the application of nitrogenous fertilizers, nitrate leaching, removal of agricultural products, and building up of soil organic matter [95]. Acidity is a chemical that contributes to soil erosion brought on by acid rain; acid rain is the term used to describe acid accumulation. Sulfur dioxide (SO2), ammonia (NH3), and nitrogen oxides (NOx), which are produced when fossil fuels are burned, are examples of acid emissions and acidic particles occur when complex chemical reactions occur in air and chemicals. dead. They fall to the earth in the form of wet precipitations such as rain, snow, clouds and fog, or dry precipitations such as dry particles and gases [49]. The survival ability of rhizobia is affected by the acidity of the soil. According to Slattery et al. [84] state that increasing aluminum amount affects rhizobial growth, disrupts nodule formation and nitrogen fixation process. Acidity changes the soil's microbial community, which lessens the impact of the rhizosphere and roots. It minimizes the cycling of nutrients and the breakdown of organic materials [83].

2.6 Biodegradation

Organic matter is temporary in soil. When soil is lost through natural processes such as mineralization, the overall activity of the soil is disrupted at the rate at which plants can regenerate the soil. This occurs on most agricultural lands [88].

In some cases, bacteria themselves can become pathogens; infectious diseases that specifically affect humans, animals, or plants. Human and animal diseases are often associated with runoff from livestock, sewage, or municipal sewage discharge into the ground and discharge of sewage into the ground due to runoff or high-water tables [26, 27, 87]. Impacts on soil biology can be measured using community diversity. Utilizing "countable" techniques, bacteria and viruses can be assessed; this often entails plating on nutrient-rich agar. These techniques, yet, are difficult and can produce incorrect outcomes. A set of values that represent abundance (diverse species), fairness (balanced allocation of members of various species), or a combination of the two can also be used to quantify the biological range of the microbial community found in soil. By monitoring soil enzymes, nutritional components, cellulose or wood decomposition, and respiration, one may evaluate nutrient cycling. Name the ailments. Toxins may develop if the microbiological life of the soil is disturbed. The soil's capacity to dechlorinate organic compounds will be impacted, especially in an anaerobic environment that is sulfate-rich. Many animals use low-pH soil to allow ammonium ions to accumulate and also reduce the activity of nitrifying bacteria, causing nitrite accumulation. redox state. Compaction or stagnant water can create anaerobic conditions. Oxygen diffuses only 1/10,000 times faster in soil with water-filled pores than in air-filled pores. Methane production in significant quantities has been demonstrated to ameliorate anoxic environments [55].

3 Need for Soil Regeneration

As we have discussed above in this chapter about some of the reasons and widespread consequences of soil degradation and how it affects the environment and human health, it comes down to the fact that the restoration and regeneration of the earth's soil is as crucial as oxygen for all living beings. The regeneration of soil is a must in order to protect the earth's diverse ecosystems like plants, animals, marine life, etc. As everything is co-dependent on each other. Regeneration of soil also paves the way for reversing the pollution in the earth by which we can restore the environment as healthy as possible for a better life for all living creatures. Mainly regeneration of the soil helps in increased productivity of crops in agriculture, helps the soil to retain a good amount of moisture and nutrients and also helps in reduced use of fertilizers and other chemicals.

Let us further discuss different ways we can regenerate soil and restore its capability to sustain life. Here let's look into regenerative agriculture and agronomic practices which are widely used for soil regeneration and lastly few soil regenerative engineering practices.

4 Future-Oriented Strategy for Soil Regrowth and Environmental Protection

4.1 Regenerative Agriculture

Regenerative agriculture has been suggested as a substitute for conventional production of food that may have less negative or even beneficial effects on the environment or society [74]. According to Project Drawdown, "regenerative agriculture promotes output by remediating soil health and maintaining its carbon content. It is totally opposed to traditional agriculture [68].) CO_2 by the year 2050. However, certain observers are growing more sceptical about the ability of regenerative agriculture to advance the cause of sustainable development [51, 70]. Let us discuss some of the agronomic practices.

4.2 Crop Rotation

The majority of plant species chosen as possible candidates for phytorestoration have been investigated in monocultures. Different agricultural approaches, however, might have a big impact on things like phytoremediation, soil extraction or immobilization, pollutant control, and soil quality and protection. Additionally, this may be crucial for plant productivity. These include enhancing biodiversity, controlling pests, and nutrition. Due to disease, pests, weeds, and nutrient depletion, monoculture can cause a decline in biomass production. It adversely affects soil fertility [23, 43, 53].

Crop rotation has been the process of planting several crops in succession on the same plot of land in order to enhance soil health, maximise nutrient content, and reduce insect and weed load. The effect of the harvest that came before it may be positive, negative, or neutral. As a result, choosing the right crops is important since some plants can change the soil's chemical, physical, and biological properties, a specific order is essential. Crop rotation is seen as a twofold approach to enhancing soil quality [36].

Agricultural growth is significantly influenced by soil Nitrogen and water conditions, which must be coordinated both geographically and dynamically [16]. Legume-based cropping systems boost soil nutrients through the biological nitrogen fixation of leguminous plants, which not only increases grain production [81]. The most widely cultivated annual legumes are the pea *(Pisum sativum L.)* chickpea *(Cicer arietinum L.)* and lentil *(Lens culinaris Medikus),* which have N2 fixation rates of 54, 52, and 49 kg N ha-1 year-1, respectively [46]. Legumes frequently experience a variety of biotic stressors, making them vulnerable to pathogenic organisms and illnesses such as Ascochyta blight, which is brought on *by Ascochyta rabiei, Colletotrichum lentis,* and *Aphanomyces euteiches.* In order to control these pests chemical pesticides were used, but due to over usage of chemical pesticides the problem of soil pollution begun [4].

Some annual crops can be used in crop rotation programs where they help to manage pests, diseases, and weeds. Deep-rooted crops can be used to target deeper impurities or promote a more thorough and deeper usage of soil resources. Growing Salix before a wheat crop considerably reduced the Cd levels in the soil and the wheat grain in a field research in Sweden [42]. But the opposite result could also happen in short-term phytoextraction studies. In a pot experiment, [69] discovered that after two years of phytoextraction with Salix smithiana, the shoot uptake of Cd and Zn by a subsequent crop of barley was significantly increased on four out of seven different soils. This implies that, relative to the amount taken from the labile pool, extracts of roots could dissolve greater quantities of metals at the start of plant extraction. In this situation, lengthier crop rotation durations are necessary. A study was conducted by Jinhao Zhang et al., on crop rotation of marigolds and Chinese cabbage. *Plasmodiophora brassicae*-caused clubroot is an economically significant soilborne disease of Chinese cabbage globally. As a result of their research, it is possible to use marigold as a trap plant to prevent and eradicate clubroot in Chinese cabbage. The germination and death of *P. brassicae* dormant spores were all significantly accelerated in vitro by marigold powder, crude extract, and root exudates. It was noted that it also provides a novel strategy for sustainable agriculture and the efficient control and prevention of the clubroot disease that affects cruciferous vegetables [103].

here are some other practices as mentioned here below:

Strip cropping: With this technique, the same field is planted with crops and cover crops in alternating rows over the same amount of time.

Contour farming: the process of farming slopes along a particular height to catch rainwater and prevent soil erosion.

Terrace Farming: Terraces are used in farming on sloping terrain to serve as walls and stop soil erosion.

Mulching: coating the soil's top layer with organic materials like straw, grass, and stones or inorganic materials like plastic. Mulch serves to preserve soil moisture, enhance soil fertility and health, and inhibit weed growth.

Tree planting: To stop soil erosion, plant trees on steep slopes, barren areas, and the boundaries of fields and increase soil water-holding capacity. The increase in forest area and indiscriminate logging must be stopped [21].

4.3 Agroforestry

According to [32], agroforestry is a system of environmentally friendly land management that combines the growing of trees or shrubs with the raising of animals on the same plot of land. It is a future plan for efficient soil conservation and includes a variety of techniques for reducing soil erosion, creating sustainable agricultural production systems, reducing environmental pollution, and boosting farm productivity. According to [4], the incorporation of leaf litter acts as a protective layer against soil erosion, enhances the soil's ability to retain moisture, and boosts crop output. In addition to reducing soil erosion, agroforestry also uses wood to make a number of marketable goods.

5 Land Configuration Techniques

According to the crop, farming system, soil type, topography, rainfall, etc., adopting the right land configuration and planting strategies can increase crop productivity, intercropping procedures, reduce discharge, soil and nutrient loss, water conservation, and efficient resource use and acquisition. result. Efficiency and revenue increase. Ridges and furrows, raised beds and furrows, wide beds and furrows, and soil ridges between rows are important land configuration methods.

5.1 Bioengineering Practices

Known as “the design of sustainable systems consistent with ecological principles that integrate human society and the natural environment for the benefit of all,” Bioengineering is a well-known subfield of environmental engineering [56, 57]. Natural catastrophes can be controlled via bioengineering [19, 59] as well as the restoration or reintroduction of plant and animal species to disturbed and degraded areas [70] and enhance the quality of the soil, air, and water [67, 100]. Mechanical structures must be added to biological measures in heavily degraded and crowded terrains. The choice of the preferred long-term strategy and the appropriate bioengineering procedures can vary significantly depending on the project’s intended purpose. For instance, soil or streambed erosion can cause a variety of problems, including a loss of topsoil, natural dependability, and nutrients, which reduces soil quality and, as a result, crop yields, threatening agricultural activities [34]; it may also increase the likelihood of the structural failure of bridges, roads, and rail lines [54] topographic alterations (terrain deformation) as a result of gully channel development, landslide triggering, and suffusion chance occurrences [66]; biodiversity loss, which affects flora and animal habitats [58]; reservoir silting as a result of soil erosion and sediment transport, compromising the functioning of those structures, floods [79, 86]. Strategies for controlling soil erosion charges will differ depending on the type of problem that requires attention. The present task in the use of bioengineering methods is to describe policies that meet a strict set of characteristics and advantages, particularly those that integrate herbal risk management with ecological restoration [73].

Terraces, contour embankments, check dams, gabions, diversion drains, geotextiles, and other permanent and temporary mechanical devices can be utilized [96]. Depending on the degree of erosion, soil type, topography and climate, mechanical measures are preferred [101]. Here are a few of the bioengineering practices in soil conservation.

Terracing: Terraces are earthen mounds constructed over the main slope to divide the area into homogeneous, parallel portions [8]. These designs are typically paired with channels to transfer garbage at a slower rate to the main outlet. This minimizes the slope's angle and length, lowering runoff rates and soil erosion while boosting water infiltration [25]. It is recommended for land with a slope of 33% or less, but can also be applied to land with a slope of 50-60% or less depending on the socioeconomic conditions of the specific area. In places where there is an abundance of good quality stones, it is advisable to place stone benches. Sometimes a semicircular terrace is created at the bottom of the plant, known as a crescent terrace.

Wattling: Wattling is a way of splitting the length of a slope into shorter portions, with wattles built at 5 to 7 m straight spacing up to 33% slope and 3 m vertical spacing up to 66% slope. It is ineffective on slopes more abrupt than 66%, as well as on highly loose or unstable rocks [82].

Check Dams: Check dams are useful in reducing runoff rates and preventing severe erosion in steep, wide ditches and are best suited for high-elevation sections of the watershed [52]. Such designs are less expensive, last longer, and require less care. The valley floor is kept at a depth of about 0.3 m, flat stones measuring 20 to 30 cm are utilized in the building of the dam, and a spillway is constructed in the dam's center to safely drain wastewater [72, 78]. Likewise, gabion dams are also used to treat drains in areas with sharply sloping ditches to prevent sedimentation, and erosion and conserve soil moisture.

Countour Bunding: Contour embankments, bunding, and retaining walls are constructed and utilized in locations with slopes of 2 to 6% and high average annual rainfall to retain soil moisture and decrease erosion [72].

6 Role of Nanotechnology in Sustainable Agriculture

Undoubtedly, the sustainable expansion of agriculture is entirely dependent on new and inventive techniques such as nanotechnology. This has various unique electronic association, plasmonic, and optical capabilities that are connected to quantum confinement effects, such as the modification of electronic energy levels caused by the surface area to volume ratio [89]

Nanomaterials are environmentally sustainable, and substantial developments in green nanotechnology have been made. In the current decade, there is a faster transition towards the green nano for the realization of its functions. The agriculture industry has a high demand for rapid, dependable, and low-cost technologies for detecting, monitoring and diagnosing biological host molecules in the agricultural sector. Nanomaterials are environmentally sustainable, and substantial developments in green nanotechnology have been made [97]. Nanopesticides and and nanofertilizers can help with insect control, plant nourishment, and ecologically friendly manufacturing methods [17]. Nanoparticles can directly attack infections and influence seed and plant metabolism, strengthening the innate immune system, changing hormone production, and increasing plant resilience to diseases and abiotic stress. [63]. Smart nutrition delivery, bioseparation of proteins, quick sampling of biological and chemical pollutants, nanoencapsulation of nutraceuticals, solubilization, and distribution are some of the new topics in food nanotechnology that can be greatly improved [85].

One of the applications of nanotechnology is seed nano-priming has favourable impacts on plant metabolism and development, it can boost the yield of several crop species. In wheat plants, Yasmeen et al. [102]. demonstrated that seed priming with iron and copper nanomaterials enhanced spike length, grain number per spike, and grain weight. According to Pereira et al. [64], priming tomato seeds with alginate/chitosan nanoparticles containing gibberellic acid significantly increased fruit yield, nearly quadrupling productivity. The potential advantages of priming watermelon seeds with biogenic silver nanoparticles made from onion extracts were demonstrated by Acharya et al. The findings showed a spike in plant growth and increased metabolic activity during the course of the plant's life, leading to an increase in production between 31.6–35.6% [1].

Agriculture can make use of nanodevices by developing more productive and less contaminated agrochemicals employing nanocarriers and smart delivery systems for sustained delivery. These nanoformulations come with various perks, including active component protection, enhanced solubilization, and easier penetration and internalization into the plant and target organism tissues [7]. A low quantity of ROS is known to operate as a signal that encourages plant growth, development, and defence mechanisms, while over-accumulation of reactive oxygen species under environmental stress causes damage to cell membranes, DNA, proteins, and other cell components, resulting in plant growth inhibition. Nanomaterials with antioxidant enzyme activity improve plants' ability to scavenge ROS, which enhances plant tolerance to abiotic stress and hence increases yield [40].

Another study on seed priming and increased germination in *Citrus lanatus* found that the seed germination frequency at 14 days was higher in Ag NP treated seeds than in the other treatment. They discovered that the level of glucose and fructose was increased during germination in Ag NP treated seeds after 96 h [1]. A recent study on Vigna radiata discovered that TiO2 NPs derived from a seed extract of *Trachyspermum ammi* considerably increased *V. radiata* growth in both in vitro and in vivo circumstances [90].

Nanotechnology, in general, provides the most promising potential for the development of new and enhanced goods. Yet, for many scientific communities, public concern about health dangers related with nanotechnology products is being investigated further [38].

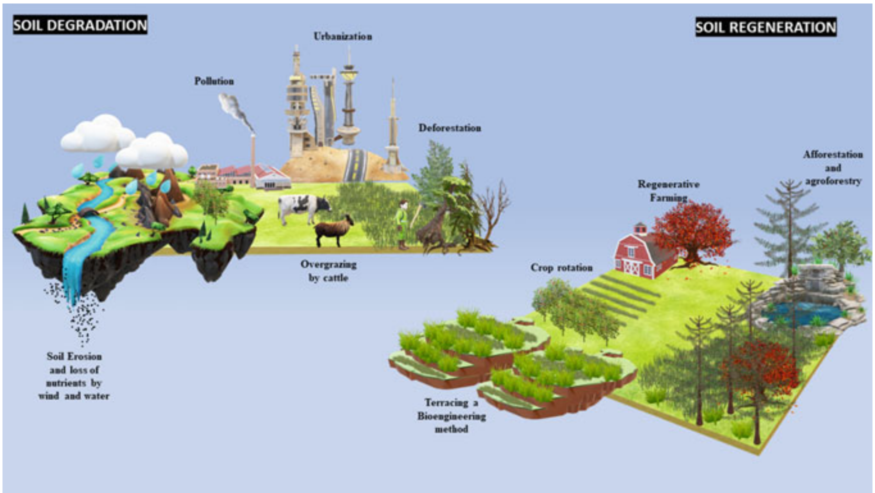

Fig. 18.1 Causes of soil degradation and methods for soil regeneration

7 Conclusion

A comprehensive and cooperative approach that integrates scientific innovation, policy support, education, and a common commitment to protecting our planet's natural resources is essential for environmental conservation and soil regeneration in the future. We can build a future that is more robust and sustainable for both our ecosystems and the next generation by embracing these trends and cooperating.

The general public is becoming more aware of the significance of soil health and environmental preservation. Programs for education and communication will remain essential in encouraging farmers, landowners, and the general public to adopt sustainable practices. Several significant trends and areas of emphasis are likely to determine the course of these critical undertakings. To implement and scale up soil regeneration strategies, stakeholders such as farmers, researchers, environmental organizations, and legislators will need to work together.

The strategies used to achieve environment conservation is the main focus of this chapter. Currently used techniques include using Bioengineering practices, enhancing the nutritional value of agricultural soil by the use of biofertilizers, utilizing nanotechnology to improve farming, Land Configuration Techniques etc. Despite the fact that there are numerous approaches to enhance the agricultural system, we still require more advanced technologies to improve soil health.

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