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Biofilms communities in the soil: characteristic and interactions using mathematical model

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ABSTRACT

There are many different kinds of microorganisms in the soil, and many of them are biofilms because they can make supracellular compounds. Surface-associated microorganisms in a biofilm are encased in a hydrated extracellular polymeric substance that aids in adherence and survival. Numerous different kinds of microorganisms call the soil home. Strong interactions with and among species are made possible by biofilms; this, in turn, might increase the effectiveness with which organic compounds and poisons in soil are degraded. This encouraged us to take a close look at soil biofilm ecosystems, which we do in this paper. In this research, we will look at how soil biofilms arise and how that affects the composition of microbial communities and their function in the soil. Recent years have seen an uptick in interest in questions about biofilm structure and the social interactions of various bacteria. Many concepts elucidating the underlying mathematics of biofilm growth are also presented. Since biofilms are so widespread, this breakthrough in soil biofilm inquiry might help scientists understand soil microbiomes better. Mathematical models further extrapolate the relationships between microbial communities and gives a more precise information as to what is happening in a biofilm. Biofilms can help plants cope with a variety of environmental challenges. Soil quality, plant nourishment, plant protection, bioremediation, and climate change are all influenced by the interplay of biofilm communities. Thus, biofilms play an important role in the development of environmentally friendly and sustainable agriculture.

1. Introduction

It has been estimated that nearly all bacteria (99 percent) exist in biofilms [1]. Soil is home to a wide variety of microorganisms. More and more evidence suggests that microorganisms found in the soil mostly adopt a sessile lifestyle as well [2]. Whether they are composed of a single species or a community of organisms, it has been found that soil biofilms may colonize a wide range of substrates and interfaces, from mineral surfaces and pore spaces to plant roots [3]. During biofilm development, cells release extracellular polymeric substances (EPS) that function as scaffolds for the biofilm matrix [4].

Biofilms have an advantage over free-living cells because of their sessile lifestyles, which allow them to gain adaptation in transpiration and boost possibilities for horizontal gene transfer [5]. However, the local soil's physicochemical features are altered due to the creation of soil biofilms. For instance, biofilm growth can impact water permeability by blocking soil pores with bioclogging organisms [6]. Biofilms' EPS boosts the cohesiveness of soil microaggregates from the inside out [7]. Since soil biofilms increase microbial survival during periods of environmental stress, they play a decisive role in the formation of soil microenvironments. Despite widespread acceptance that soil biofilms defend against environmental risks like grazing, desiccation, and even heavy metals, there are still fundamental concerns to be solved [7]. For example, the formation of soil biofilms in the soil matrix, the environmental and biological conditions that promote their growth, and the impact of soil biofilms on microbial metabolism and community composition are all poorly understood. Standardized approaches for characterizing biofilms, including free-living cells within soil matrices, were also lacking. One recent attempt was made to remove planktonic as well as biofilm cells from natural soils by washing them away (Bystriansk et al., 2019). It was found that certain organisms are completely adapted to living in plankton.

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Because of the interplay between biofilms and free-living soil organisms, it is challenging to separate their individual impacts on microbial metabolism.

2. Characteristics of soil biofilms

Multispecies biofilms, in which bacteria inhabit microhabitats, occupy only 10–6% of the soil surface area [8] and less than 1 % of the soil's total volume. To stick to biotic surfaces like stems and fungal hyphae or decomposing organic waste, microbial communities in soil biofilms produce a unique extracellular polymeric substance (EPS) [2].

Biofilms can stabilize the conditions around bacteria, shielding them against predators, drying out, and antibiotics while also increasing the availability of oxygen and nutrients and offering a niche to earn horizontal gene transfer (Madsen et al., 2012), all in spite of the complicated nature and flexibility of soil circumstances.

2.1. The soil microbiome and biofilms

Microorganisms, the earliest forms of life to arise on Earth, have had a profound impact on the planet's history and the progress of human civilization (Dodd et al., 2017). The microorganisms in a given soil its microbiome have been called the “engine” behind a number of crucial biogeochemical cycles. The microbiology of landscapes has been linked, either directly or indirectly, to the health of plants and animals [9,10]. Liang and Balser (2017) found that the soil microbiome plays an important role in carbon storage, the cycling of nutrients, and soil fertility.

In the very beginnings of microbiological research, it was usual practice to swing a flask holding the inoculum and culture medium under controlled conditions. This aids in the uptake of nutrients essential for the development and proliferation of aquatic cells. In nature, microorganisms often produce biofilms, which are structures adhering to surfaces (Flemming et al., 2016). Soil biofilms aggregate EPS when they colonize carbon-rich surfaces like plant roots and clay minerals [11]. In reaction to decreased water availability, a distinguishing aspect of the local environment, soil bacteria form multicellular aggregates termed soil biofilms [7].

2.2. Organization of soil microbial communities

There are researchers that study the soil microbiome who simply assume that the bacteria found there are continually interacting with one another [12]. However, it is not the lifestyle of soil microorganisms. Heterogeneity and diversity are hallmarks of soil ecosystems [13]. The spatial organization of soil creates a wide variety of microhabitats, each of which has the potential to support microorganisms with unique requirements. Soil bacteria are shown to exist as separate microaggregates, as evidenced by recent sectioning of intact soil samples [14].

Isolated by distances on the order of tens of micrometers, these micro-aggregates contain little more than a few hundred cells and a handful of species at most [15]. In unsaturated conditions, a single aggregation may include thousands of microorganisms from different communities, according to studies. Microbial communities in soil are like disconnected biogeographical islands; they enable microscale spatial and metabolic heterogeneity.

3. Soil biofilms

The life cycle of a soil biofilm consists of many stages: i) attachment to solid surfaces (such as minerals as well as plant roots); ii) absorption of these surfaces; iii) development and expansion; iv) maturity; and v) cell dispersal. Surface charge, ion solubility, and fluid dynamics are all factors in the physicochemical process of attachment, as described by Cai et al. (2013). When microorganisms come into contact with a surface, they undergo rapid physiologic changes at the interface that stimulate colonization (O'Toole and Wong, 2016). During biofilm development, the organisms' physiology changes, resulting in phenotypes and morphologies that are biologically distinct from their watery relatives. The composition and structure of a biofilm have stabilized to a great degree after it has attained maturity. In response to a lack of nutrients or other disturbances, bacteria inside the cell membrane can release acids that dissolve the biofilm, scattering the cells within it [16]. During biofilm dispersion, cells may actively or passively detach from the bacterial matrix. The colony may move to the newly-found place, where the propolis cycle can begin again.

3.1. Distinct characteristics of soil biofilms

Kragh et al. (2016) found that bacteria living in biofilms had a large fitness advantage over their planktonic counterparts. In these biofilms, found in soil hotspots, powerful biogeochemical processes take place with far-reaching ecological consequences [13]. Biofilm soils containing *Bradyrhizobium japonicum*, *Penicillium*, and *Penicillium* spp. (also known as Sen and Jayasinghearachchi, 2005) increased the breakdown of inorganic nutrients like phosphorus and showed higher nitrogenase activity even under high NO3 levels. Species interactions among the biofilm's major taxonomic divisions have a beneficial effect on soil aggregation [17]. The EPS that makes approximately 80 % of biofilm's dry mass [18] may protect microorganisms against biotic and abiotic stresses in soils [19], among other possible functions. Adding EPS to soil has the potential to greatly increase water retention since EPS may hold up to 20 times its weight in water [20]. To what degree EPS contributes to the formation and durability of soil aggregates is dependent on both the composition of the EPS and the soil's physicochemical properties ([21]; Büks and Kaupenjohann, 2016). Research on bacterial biofilms and their interactions has mostly been directed towards applications in biotechnology and therapeutically significant areas [22,23] rather than the meaning of soil biofilms. Research in a wide range of fields is needed to provide a solid foundation for investigating soil biofilms, which is essential for bringing soil microbiology into the modern era.

3.2. Microbial interactions in soil biofilms

Due to the close proximity of cells in biofilms, the study of their interactions and social behaviors has been given the anthropomorphic name “sociomicrobiology” [24]. Communication, the exchange of physiological products, and cell-to-cell signaling are all examples of interspecific interactions that contribute to cooperative outcomes (Burmlle et al., 2014; [12]). Soil biofilms depend on the intricate interactions of a diverse array of microorganisms that make up their underlying populations for their formation, maintenance, and function.

3.2.1. Cooperative interactions

Biofilms are communities of bacteria that have formed via natural processes [25]. Because biofilm production is beneficial to protection against environmental shocks, microbes may construct multi-species biofilms that may adapt to unfavorable living conditions together. A dual-species biofilm with strain-specific features was found to form when *Pseudomonas putida* SB5 promoted the development of *Chryseobacterium* sp. SB9. *Xanthomonas retroflexus, Paenibacillus amylolyticus, Stenotrophomonas rhizophila,* and *Microbacterium oxydans* were found to produce a multi-species biofilm, with *Xanthomonas* 024 playing a dominating role and the other strains playing a supplemental function [26].

Bacteria in biofilms need to be in close proximity to one another so that they can exchange chemicals. Bacteria that use the nitrogen- or amino acid-containing metabolites of other species in order to develop in the lab or in the wild are known ecologically as engaging in cross-feeding [27].

It is believed that the exchange of metabolites across species in biofilms is necessary to their survival due to the predominance of auxotrophic bacteria in biofilms; more than 98 % of sequenced microorganisms lack vital pathways for key genes for the production of amino acids [28]. Liquid ammonia-oxidizing organisms, such as *Nitrospira moscoviensis*, may aid ammonia-oxidizers by supplying their needs with urea (Flemming et al., 2016). Cross-feeding may be seen even in interactions between organisms from different domains, such as those between *Streptococcus mutans* and *Candida albicans*. In biofilms originating in early childhood caries, *C. albicans* and *S. mutans coexist,* with *C. albicans* feeding off of the lactic acid production of the latter [29,30].

These interactions contribute to the evolution of antibiotic and surfactant resistance in biofilms (Olsen, 2015). It has been suggested that certain types of bacteria may work together to breakdown pollutants such as the herbicide linuron and 2,4-dichlorophenoxyacetic acid (Flemming, 2010).

4. Mathematical model for growth

Let consider Bacteria fungal and Algae interaction in a Biofilm community on surface of soil.

4.1. Bacterial–fungal interaction

The interaction between bacteria and fungi within a biofilm community can be modeled using the Lotka-Volterra competition model. The equations for bacterial and fungal population dynamics are as follows:

$$\frac{\mathrm{dB}}{dt} = rB \times B\left(1 - \left(\frac{\mathrm{B}}{kB}\right)\right) + \alpha\mathrm{BF} \times B \times F) \tag{1}$$

$$\frac{\mathrm{dF}}{dt} = rF \times F\left(1 - \left(\frac{\mathrm{F}}{kF}\right)\right) - \beta\mathrm{FB} \times B \times F) \tag{2}$$

where:

B = the population sizes of bacteria

F = the population sizes of fungi

t = time,

rB = the intrinsic growth rates of bacteria

rF = the intrinsic growth rates of fungi

KB = the carrying capacities of bacteria

KF = the carrying capacities of fungi

αBF = are the interaction coefficients representing the effect of bacteria on fungal growth

βFB = the interaction coefficients representing the effect of fungi on bacterial

4.2. Bacterial–algal interaction

The interaction between bacteria and algae in a biofilm community can involve both competition and cooperation. The equations for bacterial and algal population dynamics are as follows:

$$\begin{aligned}\frac{\mathrm{dB}}{dt} &= rB \times B\left(1 - \left(\frac{\mathrm{B}}{kB}\right)\right)\\ &\quad + \alpha\mathrm{BA} \times B \times A - \delta\mathrm{BA} \times B \times A\end{aligned} \tag{3}$$

$$\begin{aligned}\frac{\mathrm{dA}}{dt} &= rA \times A\left(1 - \left(\frac{\mathrm{A}}{kA}\right)\right)\\ &\quad - \beta\mathrm{AB} \times A \times B + \gamma\mathrm{AB} \times A \times B\end{aligned} \tag{4}$$

where:

B = are the population sizes of bacteria

A = the population sizes of algae

t = time,

rB = the intrinsic growth rates of bacteria

rA = the intrinsic growth rates of algae

KB = the carrying capacities of bacteria

KA = the carrying capacities of algae

αBA = are the competition coefficients representing the negative effect of bacteria

βAB = the competition coefficients representing the negative effect of algae on bacterial growth

δBA = the cooperation coefficients representing the positive effect of bacteria on algal growth

γAB = the cooperation coefficients representing the positive effect of algae on bacterial growth

4.3. Algal–fungal interaction

The interaction between algae and fungi can be modeled using the Lotka-Volterra competition model or other interaction models. The equations for algal and fungal population dynamics are as follows:

$$\begin{aligned}\frac{\mathrm{dA}}{dt} &= rA \times A\left(1 - \left(\frac{\mathrm{A}}{kA}\right)\right)\\ &\quad + \alpha\mathrm{AF} \times A \times F - \beta\mathrm{FA} \times F \times A\\ \frac{\mathrm{dF}}{dt} &= rF \times F\left(1 - \left(\frac{\mathrm{F}}{kF}\right)\right)\\ &\quad + \alpha\mathrm{FA} \times F \times A - \beta\mathrm{FA} \times A \times F\end{aligned}$$

where:
A = are the population sizes of algae and fungi
F = the population sizes of fungi
t = time
rA = the intrinsic growth rates of algae
rF = the intrinsic growth rates of fungi
KA = are the carrying capacities of algae
KF = the carrying capacities of fungi
AF = the competition coefficients representing the negative effect of algae on fungal growth
βAF = the competition coefficients representing the negative effect of fungi on algal growth
αFA = the cooperation coefficients representing the positive effect of algae on fungal growth
βFA = the cooperation coefficients representing the positive effect of fungi on algal growth

These equations capture the interactions between bacteria, fungi, and algae within biofilm communities. The specific values of the parameters (ri, Ki, αij, βij, δij, γij) should be estimated based on experimental data or literature values for the particular microbial community and interaction being studied.

It's important to note that these equations provide a simplified representation of microbial interactions, and the actual dynamics can be more complex in real-world systems. Additional factors, such as nutrient availability, environmental conditions, and spatial dynamics, can also be incorporated into the model to better capture the complexity of microbial interactions in biofilms.

4.4. Mathematical model for nutrient availability

The availability of nutrients in the soil environment is an essential factor that influences microbial growth and interactions. Nutrient dynamics can be modeled using diffusion-reaction equations, considering nutrient diffusion, uptake, and consumption by microbial populations. Here is a simplified form of the equation:

$$\frac{\partial C_1}{\partial t} = D_1 \nabla^2 C_1 - \mathrm{U}\left(C_1\right) \times \mathrm{B}$$
$$\frac{\partial C_2}{\partial t} = D_2 \nabla^2 C_2 - \mathrm{U}\left(C_2\right) \times \mathrm{B}$$
$$\frac{\partial C_3}{\partial t} = D_3 \nabla^2 C_3 - \mathrm{U}\left(C_3\right) \times \mathrm{B}$$

where:

C_1 = the concentration of the nutrient for bacteria
C_2 = the concentration of the nutrient for Fungal
C_3 = the concentration of the nutrient for Algae,
t is time,
D_1 is the diffusion coefficient for Bacteria
D_2 is the diffusion coefficient for Fungal
D_3 is the diffusion coefficient for Algae
∇^2 is the Laplacian operator,
U(2 C) is the microbial nutrient uptake function for Fungal
U(1 C) is the microbial nutrient uptake function for Bacteria
U(3 C) is the microbial nutrient uptake function for Algae
B represents the bacteria population
F represents the fungal population.
A represents the fungal population.

4.5. Mathematical model for competition

Microbial species within biofilm communities can compete for limited resources such as nutrients and space. The Lotka-Volterra competition model can be used to describe the dynamics of competing microbial species. The equations are as follows:

$$\frac{\mathrm{dB}}{dt} = r_1 \times B_1\left(1 - \frac{\left(B + \alpha_{123} \times \mathrm{N}_2\right)}{k_1}\right.$$
$$\frac{\mathrm{dF}}{dt} = r_2 \times F_2\left(1 - \frac{\left(F + \alpha_{213} \times \mathrm{N}_1\right)}{k_2}\right.$$
$$\frac{\mathrm{dA}}{dt} = r_3 \times A_{31}\left(1 - \frac{\left(A + \alpha_{312} \times \mathrm{N}_2\right)}{k_1}\right.$$

where:

B = the population sizes of Bacteria and Fungai

F = the population sizes of Fungal and Algae

A = the population sizes of Algae and Bacteria

t is time,

r1 are the intrinsic growth rates of Bacteria

r2 are the intrinsic growth rates of Fungal

r3 are the intrinsic growth rates of Algae

α123 are the competition coefficients representing the effect of Bacteria on the growth rate of the Fungal and Algae,

α213 are the competition coefficients representing the effect of Fungal on the growth rate of the Bacteria and Algae

α312 are the competition coefficients representing the effect of Algae on the growth rate of the Bacteria and fungal

K1 are the carrying capacities of Bacteria

K2 the carrying capacities of Fungal

K3 are the carrying capacities of Algae

4.6. Mathematical model for microbial growth

The growth of microbial populations within biofilms can be modeled using population dynamics equations. The logistic growth model is commonly used to describe microbial growth. The equation is as follows:

$$\frac{\mathrm{dB}}{dt} = r_1 \times B\left(1 - \left(\frac{B}{k_1}\right)\right)$$
$$\frac{\mathrm{dF}}{dt} = r_2 \times F\left(1 - \left(\frac{F}{k_2}\right)\right)$$
$$\frac{\mathrm{dA}}{dt} = r_3 \times A\left(1 - \left(\frac{A}{k_3}\right)\right)$$

where:

B is the population size of the Bacteria

F is the population size of the Fungal

A is the population size of the Algae

t is time

r1 is the intrinsic growth rate of Bacteria

r2 is the intrinsic growth rate of Fungal

r3 is the intrinsic growth rate of Algae

K1 is the carrying capacity of the environment for Bacteria

K2 is the carrying capacity of the environment for Fungal

K3 is the carrying capacity of the environment for Algae

5. The rhizosphere

The microbiome and plant health are profoundly impacted by the intricately regulated symbiotic connections among plants and the associated bacteria [31]. Invading the rhizosphere, plant-beneficial bacteria build biofilms that aid in plant development, nutrient cycling, biological prevention of plant diseases, soil pollution resistance, and soil bioremediation [32]. Additional study utilizing metagenomics approaches is required to better determine the role(s) underlying rhizosphere biofilms for specific soil applications [33].

Soil quality and plant development may be improved by ectomycorrhizal fungi (EMF) and arbuscular mycorrhizal fungi (AMF), two additional key microbial symbiont groups in the plant microbiome [34,35]. Many different kinds of bacteria have been discovered living in and on mycorrhizal fungi, such as spores [36]. Mycorrhiza-associated bacteria help roots grow by facilitating sporulation, mycelial establishment, and growth, shielding the fungus from antagonistic substances, promoting traits such as nitrogen fixation, phosphate solubilization, antibacterial or antifungal properties, and improving recognition between roots and AMF fungi [37]. By altering the fungal structures or supplying citric and maleic acid as carbon sources, these bacteria may modify AMF (through bipartite interaction) and play a critical role in bacterial-mycorrhizal contact and signaling [38]. The survival of these microbes does not rely on mycorrhizal symbiosis.

It is probable that the symbiotic interaction between plants, fungi, and bacteria has existed since the appearance of the earliest vascular plants, since there are many different types of microorganisms living in close proximity to plant roots in the wild. Future initiatives to boost agricultural productivity need a deeper understanding of the signaling communication techniques employed by natural microbial communities to impact plants, such as quorum sensing and trophic-mediated communication [39]. Scientists are employing next-generation sequencing and metagenomics techniques to perform a mechanistic investigation of the microbial communities associated with plants in order to better understand the physiological potential of plants.

5.1. Importance of biofilms

Bacteria living in biofilms benefit from a number of conditions, including protection from osmotic shock, ultraviolet radiation, modifications to pH, dehydration, and exposure to antimicrobial agents [40]. To prevent the biofilm from drying up and being penetrated by toxins, the matrix provides a hydrated barrier between the bacteria and the outside environment (Flemming, 2016). Thus, biofilms, which serve to stabilize cells, protect them from the stresses of physicochemical changes, and facilitate the exchange of genetic information, are the responsibility of EPS and need its constant maintenance. Despite living in unfavorable conditions, microorganisms' chances of growth and survival, including metabolism, are improved by biofilms. Highly coordinated, friendly, and communicative cellular activities are hallmarks of responsive biological films.

5.2. Biofilm types in the environment

In nature, microbes compete for food, space, and other resources [41]. Bacterial colonies form bonds with surfaces and then grow into shapes as basic as a sphere or as complicated as a mushroom. Carbon availability, flow rate, and oxygen gradient all play roles in shaping bacterial communities [42]. Initially, just a single bacterium will cling to the surface, but within a few generations, it will have divided several times and become a microcolony. The mechanical processes that lead to the formation of a microcolony include the action of cell stretching factors, the rearrangement of cells, adhesion, friction, and steric contact. Although bacterial microcolonies typically grow inside a monolayer, they may quickly transition into foam structures at the liquid–solid interface [43].

5.3. Biofilms in plant-associated habitats

The rhizosphere is altered by the roots and root exudates in the soil, and it is subsequently colonized by bacteria that migrate from the bulk soil to the rhizoplane. Burkholderia, Paenibacillus, Bacillus, and Pseudomonas are just a few of the organisms that have been shown to interact with plant roots in a positive way. These associations are crucial for bacterial communication and successful root colonization.

5.4. Formation of biofilm on plants

In spite of adverse conditions, signals including water and nutrients availability and bacterial–bacterial interactions may stimulate root growth (Zuniga et al., 2017). Root surface qualities vary across the length of the roots, and biofilm formation is influenced by exudates and nutrients produced by the roots at different locations. Timmusk et al. [44] observed that the matured root zone was more densely colonized by organisms than the root hairs, the area between split cells, and the root crown.

5.5. Root biofilm

Pseudomonas biofilms were shown to have a positive influence on plant development and production when they formed on the taproot of *Arabidopsis thaliana* [45]. The chemical composition of the root milky material may have an effect on the bacterial population in the rhizosphere. Mhlongo et al. [39] found the two types of nicotine from bananas as well as the citrus acid from cucumber roots attracted and encouraged biofilm formation by *Bacillus subtilis* N11. *B. subtilis* biofilm colonization, adhesion, and development on *A. thaliana* plant roots were found to depend on the existence of the microbial TasA protein and exopolysaccharide. Xylan, Pectin, and arabinogalactan are only some of the vegetable sugars shown to support early biofilm growth [46].

5.6. Biofilm functions relevant for agriculture biotechnology

The biofilms in the soil are a bustling hub of communication between different orders of microbes. Protecting plants against drought, salt, inorganic, and organic pollutants, among other abiotic stresses, may lead to higher crop yields if these products are used [47]. Root exudation responses under stress may be enhanced by biofilms in the rhizosphere, which may help increase water stability [48]. Biofilms may be designed to biodegrade organic pollutants and heavy metals in soil due to their protective matrix [49]. Spraying the plant's aerial parts with a favorable bacterial biofilm inoculum or adding an inoculum to the soil are both effective ways to promote plant development and growth [50].

Metabolic collaboration in the presence of fungi is essential for the creation of new bacterial niches in the soil [51]. One example is the use of fungal exudates for bacterial adhesion to the surface of the soil. The microorganisms that make up a biofilm, particularly the bacterial species, are thought to be more robust and less susceptible to abiotic forces when bacteria and fungi collaborate metabolically. Through plant–microbe interactions, mycorrhized plants may promote mycorrhization and impact the local microbial ecology [52]. Therefore, a change in nutrient cycling improves soil structure, which aids plant growth [53]. The generation of polysaccharides and bioactive compounds by multispecies biofilms may have greater positive impacts on plant growth and soil health.

5.7. The role of biofilm in biogeochemical cycle

The biofilm is thought to play an important role in nutrient transportation and availability in productive, multiple taxa were discovered to engage in biogeochemical cycles in mangroves in a synergistic manner. *Neisseria, Ruegeria, Rhodococcus, Desulfotomaculum,* and *Gordonia,* for example, were found to be synergistically involved in the carbon, nitrogen, and sulfur cycles, while *Neisseria* and *Treponema* were found to be synergistically involved in the nitrogen and sulfur cycles. Biogeochemical cycles are important components of ecosystem dynamics because they help to degrade refractory organic materials and recycle nutrients and hazardous elements like carbon, nitrogen, sulfur, and phosphorus. Human actions can either directly or indirectly affect biogeochemical cycles [51]. Changes in the biological, chemical, and physical qualities and processes of the environment are examples of direct effects. However, global warming and climate change may jeopardize the biogeochemical cycle's balance. Global warming, for example, could result in the depletion of massive organic carbon reserves in soils. Mangroves store more carbon than other major global forests. Furthermore, climate change is boosting nitrogen (N) and phosphorus (P) deliveries along the land-water continuum [45]. Climate change is projected to increase the conveyance of terrestrial biomass into bodies of water and accelerate aquatic biomass production and turnover, thus increasing the size and frequency of nutrient (P and N) release episodes. Furthermore, the sulfur cycle encourages iron deposition and phosphorus release in freshwater habitats [39]. Furthermore, numerous studies have found that microorganisms play a significant part in biogeochemical cycles. Particle-associated bacteria, for example, appear to play a far more important role in biogeochemical cycles than free-living bacteria.

5.8. Role of biofilm in the soil and its effect on agriculture

Microbial biofilms are critical in agriculture, which is facing a major challenge from climate change, which will cause many pressures on plants. However, few people understand what microbial biofilm is, how it helps plants protect themselves against stress, and how it could be developed as a biofertilizer. The goal of this work is to expose the reader to microbial biofilm, its importance for plants in stress adaptation via plant–microbe–soil interactions, and its potential for development as a biological fertilizer [54].

Soil-plantmicrobial interactions in the root system are linked to plant vulnerability to pests and diseases, as well as abiotic stressors. Plants will be able to tolerate varied pressures if the soil is healthy and has a broad variety of microbes. The rhizosphere is the zone surrounding the roots that has the most microbial activity. Roots emit a variety of compounds into the rhizosphere that are nutrient-rich and appealing to microorganisms [12], as well as microbial biofilms, which play an important role in plant development and soil health. In stressful circumstances, microbial biofilm in the root system is thought to be a survival mechanism.

Microbes can supply nutrients to plants as well as aid in their defense against infections and pests. A healthy soil microbiome regulates different enzymatic processes and biogeochemical cycles, protects plants from pests and diseases, stimulates plant development, maintains root health, aids in nutrient absorption, and boosts environmental sensitivity [54]. Biofilms are preferred by many bacteria because they provide a food source, a site for metabolite exchange, resistance to medicines and environmental challenges, and resistance to host immunological responses [7]. Nutrient availability, temperature, soil pH, humidity, surface characteristics, salinity, and microbial products all influence biofilm formation [12].

A healthy soil microbiome regulates different enzymatic processes and biogeochemical cycles, protects plants from pests and diseases, stimulates plant development, maintains root health, aids in nutrient absorption, and boosts environmental sensitivity [9].

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