Mardiana Idayu Ahmad
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Renewable Energy and Sustainable Technologies for Building and Environmental Applications

Options for a Greener Future

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Preface

This book highlights state of the art, advancements, challenges, and options in the areas of renewable energy and sustainable technologies for building environmental applications. It aims to provide insight into existing knowledge about renewable energy and sustainable technologies while demonstrating their significance to greener environmental approaches. This book contributes to significant expansions in the energy technologies' research horizons; while highlighting a paradigm shift in the research and discusses substantial improvements to renewable energy and sustainable technologies for building environmental applications.

It consists of various relevant articles from world-leading experts which are chosen exclusively to illustrate the main areas of renewable energy and sustainable technologies, arranged in 14 different chapters. Chapter 1 presents a review on the inverse problem for phase change materials and application in building envelopes. The review would serve as a useful reference for the readers who are particularly interested in studying building envelopes thermal performance design. Chapter 2 provides an overview of different types of natural polymer composite membranes and their potentials in water remediation. In Chapter 3, discusses types of polymers that can be used in the development of heat exchangers for energy recovery applications in buildings. These polymeric heat exchangers are predicted to be built upon four bases; new polymers, new reinforcement or additives, new design, and new fabrication techniques. Chapter 4 highlights the potential and limitations of the solar-induced ventilation strategy in the tropical region, particularly in its subtypes of tropical rainforest climate and tropical monsoon climate. The chapter is based on the scientific results from the previous studies, recent innovations and latest technologies associated with such ventilation strategies and several significant examples of its applications in the contemporary tropical buildings. Lighting technologies and the impact of lighting design are covered in Chapter 5. This chapter also discusses user behavior to the energy consumption of lighting and life cycle assessment of luminaires. With the aim to have an in-depth understanding of energy recovery technology for building applications, Chapter 6 presents the mechanism and the application of this technology in various climatic conditions such as winter and summer conditions; cold and extremely cold climate conditions; and hot-humid condition based on previous data in the open literature. This chapter also examines the limitations, research gaps, and future recommendations pertaining to this technological development. Chapter 7 includes a discussion on critical design concepts of toplighting systems based on natural light for building interiors in different geographical locations. This chapter also covers issues on daylight in passive and sustainable architecture.

Understanding nature and biodiversity as part of sustainable agents will be advantageous to the environment and ecosystem. With this aim, Chapter 8 addresses polychaetes as biological agents of sustainable technology for environmental applications. This chapter focuses on the distribution of polychaetes in the world, and explains its role in tackling environmental issues. Examples include, detoxifying inorganic contaminants into less toxic compounds, processing organically enriched sediments via their digestive system and overcoming hypoxia and anoxia cases plus sulphidic condition are highlighted. Chapter 9 explores the role of incorporating plants in green building designs as one of the approaches to reduce energy consumption in buildings and to mitigate global warming. The nature of plants, their characteristics, and localized setting to benefit the microclimate are discussed. A discussion on low-carbon technology concept and characteristics of turbine ventilator as eco-friendly technology is presented in Chapter 10. The mechanism and concept are discussed by taking into account conventional and hybrid designs of turbine ventilators. Due to environmental concern, research and engineering interest have been changed from using synthetic adhesive to a new biobased adhesive or self-bonding board that is free from synthetic adhesive called binderless board. With this regard, Chapter 11 presents a review on binderless board manufacturing, treatment, and other processes using oil palm biomass as raw materials. The scope of this chapter is only based on the environmental aspects without coinciding with any economic factors or costing. Chapter 12 gives an overview of the lifecycle approach in materials selection and the assessment of materials used in construction based on ISO 14040:2006 and ISO 14044:2006. Analysis of life cycle assessment on building materials adopted in mosque construction in Iraq is also presented. Chapter 13 provides a review on the prospects of algae for biofuel production. Macroalgae integration into a biorefinery is also discussed. This chapter concludes that further research must be intensified to identify novel and the most appropriate algae species with high oil contents and fast-growth rates in a specific environment in the future. Chapter 14 presents a detailed review on energy production by microorganisms such as bacterium and algae. Sustainability of energy recovery by biological process is also highlighted at the end of this chapter. This information should be useful background for the understanding of energy production comparing competing options for biological and environmental applications.

Last but not least, we would like to take this opportunity to convey our appreciation to all contributors of the articles in this book. Special thanks entrusted to all reviewers that have provided comments and recommendations to the articles contained in this book. Our special thanks to Ms. Tiffany Gasbarrini, Mr. Brian

Halm, and Ms. Zoe Kennedy from Springer US for their kind support and great efforts in bringing the book to fruition. For the Editorial Team of Springer, we express our thanks for their contribution in making this book publishable. It has been a pleasure working with the team in the publication process of this book. We hope that this book can be a valuable reference for senior undergraduate and graduate students, engineers, architects, practitioners, scientists, researchers, planners, and employees in the area of renewable energy and sustainable technologies.

January 2016

Mardiana Idayu Ahmad
Mazran Ismail
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Contents

Nomenclature

ATRP	Atomic transfer radical polymerization
BMI	Bismaleimides
BPA	Bisphenol A
DMAc	N,N-Dimethylacetamide
DMF	N,N-Dimethylformamide
DSC	Differential scanning calorimetry
ESC	Environmental stress cracking
HIPS	High impact polystyrene
LCP	Liquid crystal polymers
NMP	Nitroxide-mediated polymerization/N-methyl-2-pyrrolidone
PB	Polybutylene
PBI	Polybenzimidazoles
PC	Polycarbonate
PDI	Polydispersity index
PE	Polyethylene
PEEK	Polyether ether ketone
PEI	Polyether imide
PES	Polyether sulfone
PET	Polyethylene terephthalate
PF	Phenol formaldehyde
PFA	Perfluoroalkoxyl
PMMA	Polymethyl methacrylate
PP	Polypropylene
PPO	Polyphenylene oxide
PPS	Polyphenylene sulfide
PS	Polystyrene
PTFE	Polytetrafluoroethylene
PVC	Polyvinyl chloride
PVDF	Polyvinylidene fluoride

PVOH	Polyvinyl alcohol
RAFT	Reversible addition–fragmentation chain transfer
UP	Unsaturated polyesters
UV	Ultraviolet
VA	Vinyl acetate

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Chapter 1
Inverse Problem for Phase Change Materials and Preparation in Building Envelope

Xin Wang, Rui Yang and Saffa Riffat

Abstract Conventional methods to analyze building energy are of limitation and difficult to determine the best building envelope structure, best material thermal properties, and the best way for heating or cooling. In this paper, the research on the inverse problem for phase change materials and the application in building envelope by our group was reviewed, which can be used to guide the building envelope thermal performance design, material preparation and selection for effective use of renewable energy, reducing building operational energy consumption, increasing building thermal comfort, and reducing environment pollution and greenhouse gas emission. This paper also presents some current problems needed further research.

Keywords Sustainable energy · Energy storage · Nonlinear · SSPCM · Phase change temperature · Latent heat

1.1 Introduction

Over the past two decades, the world's primary energy usage has grown by 49 %, with an average annual increase of 2 %. Buildings account for 20–40 % of the total energy consumption [1, 2]. In order to get energy conservation and greenhouse gases reduction, renewable energy is encouraged to replace conventional fuels.

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However, renewable energy is of low energy density and intermittent, which can be solved by thermal energy storage. Effective thermal energy storage materials are required for the wider application of solar energy, which is the most abundant renewable energy source, and for novel materials development and application either.

A phase change material (PCM) is a substance with a high heat of fusion which, melting and solidifying at a certain temperature (or range), is capable of storing and releasing large amounts of energy [3]. Due to high latent heat within a narrow temperature range, PCM has more suitable features in peak shaving, tariff reduction, energy saving, equipment capacity reduction, and thermal comfort increase. The development of new material, theory, and technology brings new chances and challenges for PCM energy storage.

Figure 1.1 shows the publications numbers on the Web of Science in the recent 10 years with topic words “PCMs,” “Buildings,” and “Energy storage.” It is shown that there is a rapid increase in the related research and the number in 2014 is about 20 times of that in 2005. The use of thermal energy storage with PCM has become a great concerned topic of interest not only within the research community but also within the architects and engineers.

As the indoor and outdoor environment interface, building envelope can not only offer security, privacy, access, and view, but also adjust various forms of energy flow (light, heat, sound, humidity, etc.). The main functions of building envelope are in the following aspects: vision, lighting, shading, thermal insulation, heat preservation, ventilation, and sound insulation. Improving the form and thermal performance of building envelope is an important way for building energy conservation [4]. Cabeza et al. [5] reviewed PCMs available and problems and possible solutions on the application in buildings. Zhu et al. [6] reviewed the previous research work on dynamic characteristics and energy performance of buildings due to the integration of PCMs, especially in using PCMs for free cooling and peak load shifting. Al-abidi et al. [7] reviewed the numerical modeling of PCMs through commercial computational fluid dynamic (CFD) software and self-developed programming to study the heat transfer phenomena in PCMs. Conventional approaches are commonly used for analyzing the building envelope thermal performance in

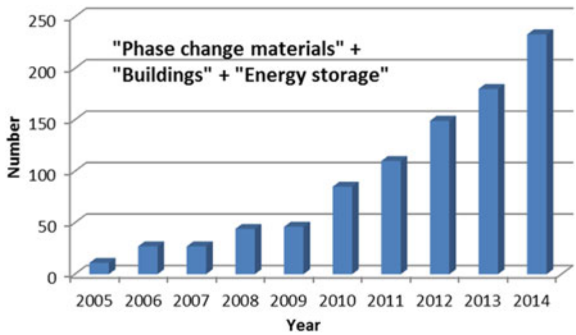

Fig. 1.1 Publications in Web of Science (2005–2014)

most of references. For a given building envelope, where the thermal properties of building material is known, thermal performances of a building are analyzed and the heating and cooling loads are supplied. This method is of limitation and difficult to determine the best building envelope structure, best material thermal properties, and the best way for heating or cooling. Thus, an inverse problem for PCMs and application in building envelop was proposed by our group, which aimed for effective use of renewable energy, reducing building operational energy consumption, increasing building thermal comfort, and reducing environment pollution and greenhouse gas emission [8–10].

Another value of the inverse problem research is to guide the building material preparation. According to the inverse problem research, the thermal performance of PCM is similar to the ideal building material, which provides the theoretical foundation. PCMs can be categorized as organic, inorganic, etc. Table 1.1 lists the main characteristics of inorganic and organic PCMs [4]. SSPCM is composed of an organic PCM, e.g., paraffin, and a polymer matrix which can encapsulate PCMs and maintain the shape no matter the PCM is in solid state or in liquid state. The SSPCM can be made into different shapes, such as grain, stick, and board.

In this paper, the inverse problem research for PCMs and application in building envelop by our group is reviewed, including the heat transfer research and SSPCM preparation research. It is very different from the conventional approaches and can be used to guide the building envelope thermal performance design and material preparation and selection. At last, this paper also presents some current problems needed further research.

Table 1.1 Classification and properties of PCMs [4]

Classification	Inorganic	Organic
Category	Crystalline hydrate, molten salt, metal, or alloy	High aliphatic hydrocarbon, acid/esters or salts, alcohols, aromatic hydrocarbons, aromatic ketone, lactam, freon, multi-carbonated category, polymers
Advantages	Higher energy storage density, higher thermal conductivity, nonflammable, inexpensive	Physical and chemical stability, good thermal behavior, adjustable transition zone
Disadvantages	Supercooling, phase segregation, corrosive	Low thermal conductivity, low density, low melting point, highly volatile, flammable, volume change
Methods for improvement	Mixed with nucleating and thickening agents, thin layer arranged horizontally, mechanical stir	High thermal conductivity additives, fire-retardant additives

1.2 Ideal Energy Conservation Building Envelope and Inverse Problems

1.2.1 Concept

The concept of ideal energy conservation building envelope was proposed in references [8, 9], which is that if the storage and insulation properties of the building envelope have a suitable role in the delay and decay for outdoor temperature fluctuations, the indoor air temperature can stay in a comfortable range without heating and air-conditioning (Fig. 1.2). The corresponding research is to study how to rely on the building envelope self-temperature regulation, fully used natural renewable energy, to meet the requirements of human thermal comfort without or with less additional conventional energy. The analysis of the building envelope linear and nonlinear thermal mass characteristics to determine the best building envelope structure, best material thermal physical properties, and suitable application conditions is a novel insight into the thermal property design and material development of building envelope.

Figure 1.3 shows the comparison of the traditional approach and the new approach for space heating and cooling. In contrast to the traditional approach (the thermophysical properties of building envelope material are known and constant so that the relating equations describing the indoor air temperature tend to be linear differential equations), the new approach solves the inverse problem (thermophysical properties, etc., of buildings are unknown), whose solution can be a function with temperature instead of a constant value [9–11].

As people wear different clothes for different seasons, the "clothes" of buildings can change with seasons [11]. But what would the ideal "clothes" for buildings be? These problems have not been well addressed in traditional studies that tend to select a single suit of "clothes" for buildings [12]. The key problem with these

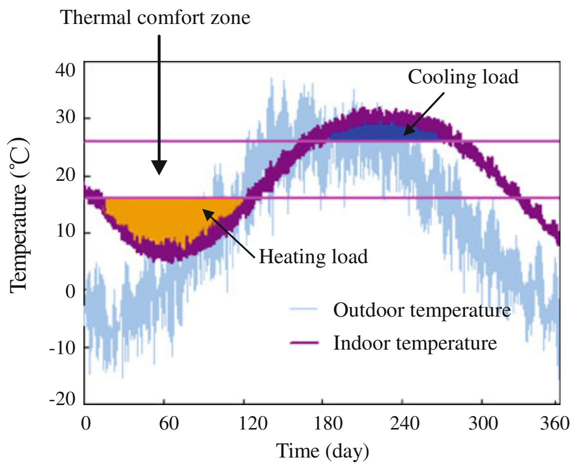

Fig. 1.2 Indoor and outdoor air temperature variation versus time [8]

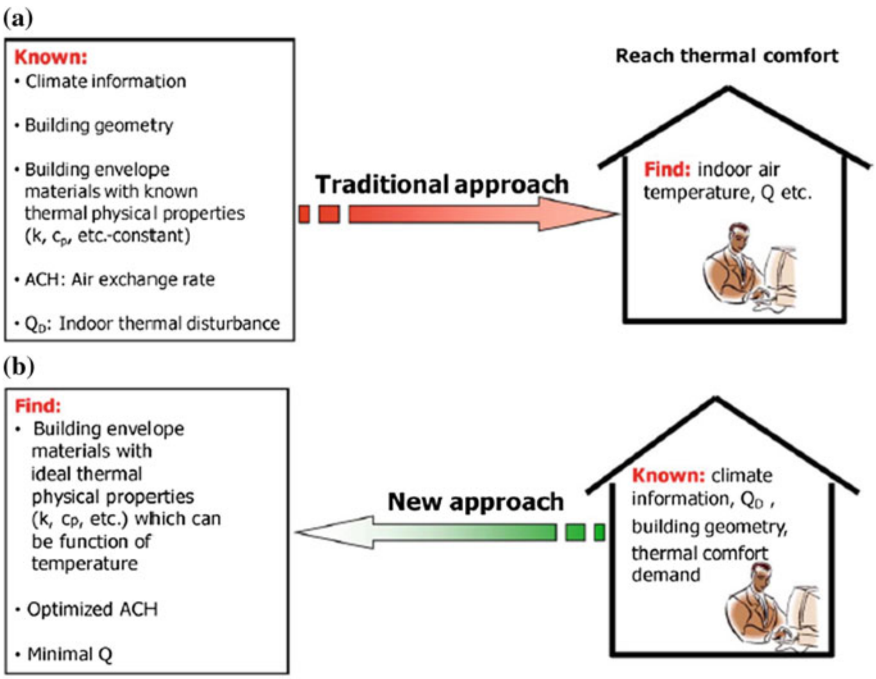

Fig. 1.3 Comparison of the traditional approach and the new approach for space heating and/or cooling: **a** traditional approach and **b** new approach [9]

studies is that the external wall is made from materials that have constant thermophysical properties, so that the thermal resistance and/or thermal capacity cannot change according to the outdoor temperature.

There are two ways to change a building's "clothes": (1) change the structure of the building's external wall, (2) adjust the thermophysical properties (i.e., volumetric specific heat $\rho c_p(t)$, thermal conductivity $k(t)$) of the building's external wall. So determining the optimal thermophysical properties of passive building external walls is interesting and needed to be solved.

1.2.2 Basic Heat Transfer Model [9]

In reference [9], the mathematic model including the two-plate model (Fig. 1.4) was set up. In this model, the internal walls, ceiling, and floor are lumped into one plate. The long wave radiations between them are ignored. The external wall is treated as another plate where a south-facing window is fixed.

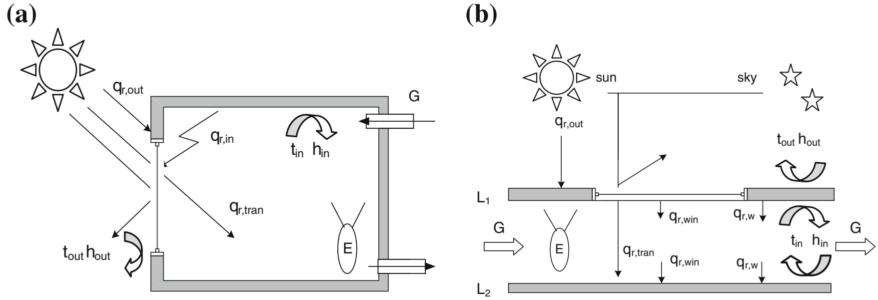

Fig. 1.4 Schematic diagram of the problem geometry (**a**) and two-plate room model (**b**) [9]

The main heat transfer equation is as follows:

$$\rho \frac{\partial H}{\partial \tau} = k \frac{\partial^2 T}{\partial x^2} \tag{1.1}$$

where enthalpy for linear physical properties of materials can be expressed as $H = \int_{t_0}^{t} c_p dt$; enthalpy for nonlinear physical properties of materials can be expressed as $H = \int_{t_0}^{t_\mathrm{L}} c_{p,\mathrm{s}} dt + \int_{t_\mathrm{L}}^{t_\mathrm{H}} c_{p,\mathrm{m}} dt + \int_{t_\mathrm{H}}^{t} c_{p,\mathrm{l}} dt$, where t is the material temperature, °C; t_0, the material temperature when the enthalpy equal 0, °C; t_L and t_H, low and high limits of the phase change temperature, °C; ρ, the density, kg/m^3; c_p, the specific heat, J/(kg K); and the subscripts s and l mean solid and liquid, respectively.

The energy balance equation of indoor air is as follows:

$$V_R \cdot \rho_a \cdot c_{p,a} \frac{\partial t_a}{\partial \tau} = \sum_{j=1}^{2} Q_{p,j} + Q_{win} + Q_{D,C} + Q_L \tag{1.2}$$

where V_R is the volume of the room, m^3; t_a, the indoor air temperature, °C; $Q_{p,j}$, convection heat transfer rate between indoor air and two plates (j = 1, 2), W; Q_{win}, convection heat transfer rate between indoor air and window, W; $Q_{D,C}$, convection heat transfer rate from the indoor heat sources, W; and Q_L, heat transfer rate by air leakage or natural ventilation, W.

Table 1.2 lists the room information.

1.2.3 Evaluation Parameters [9]

In order to evaluate the thermal comfort degree without heating and air-conditioning, the following new parameters I_{win} (integrated discomfort degree for indoor air temperature in winter), I_{sum} (integrated discomfort degree for indoor

Table 1.2 Room information [9]

Items	Values
Geometry	5.7 m (depth) × 3.6 m (width) × 3.2 m (height) One south-facing external wall, three internal walls, one ceiling, and floor
Wall	External wall: 0.25 m Internal wall, ceiling, and floor: 0.2 m, ρc_p = 1.5 MJ/m^3 °C, k = 1 W/m °C
Window	Double-glazing: 2.0 m (length) × 1.7 m (width) Overall heat transfer coefficient: 3.1 W/m^2 °C
ACH	5.0 h^{-1} (outdoor air temperature is higher than 20 °C and lower than 26 °C) 0.5 h^{-1} (other conditions)
Indoor thermal disturbance	Average value: 10.6 W/m^2
Convective heat transfer coefficients of wall	Outer surfaces: h_{out} = 23.3 W/m^2 °C Inner surfaces: h_{in} = 1.31(Δt)$^{1/3}$

air temperature in summer), and I_{year} (integrated uncomfortable degree for indoor operative temperature over a whole year) are defined as follows [9]:

$$I_{\mathrm{sum}} = \int\limits_{\mathrm{summer}} (t_{\mathrm{in,o}} - t_{\mathrm{H}})d\tau \quad t_{in,o} > t_H \tag{1.3}$$

$$I_{\mathrm{win}} = \int\limits_{\mathrm{winter}} (t_{\mathrm{L}} - t_{\mathrm{in,o}})d\tau \quad t_{in,o} < t_H \tag{1.4}$$

$$I_{\mathrm{year}} = \int\limits_{\substack{\mathrm{year} \\ t_{\mathrm{L}} > t_{\mathrm{in,o}}}} (t_{\mathrm{L}} - t_{\mathrm{in,o}})\mathrm{d}\tau + \int\limits_{\substack{\mathrm{year} \\ t_{\mathrm{in,o}} > t_{\mathrm{H}}}} (t_{\mathrm{in,o}} - t_{\mathrm{H}})\mathrm{d}\tau \tag{1.5}$$

where $t_{in,o}$ is indoor operating temperature, °C; t_H and t_L are upper and lower limits of the thermal comfort temperature zone, °C. Obviously, the room is more comfortable when I_{sum}, I_{win}, and I_{year} become smaller. When I_{year} (or I_{sum}, I_{win}) is zero, a passive ideal energy conservation building is achieved.

The upper and lower temperature limits of the thermal comfort zone t_H and t_L are set to be 28 and 16 °C, respectively.

Thus, the integrated discomfort degree for indoor operating temperature can be expressed by the following equation:

$$I = f\left(\rho c_p(t), k(t), ACH(\tau), Q(\tau)\right) \tag{1.6}$$

where $\rho c_p(t)$ is the thermal conductivity, J/(m^3 K); $k(t)$, the volumetric specific heat, W/(m K); ACH(τ), the air change per hour (h^{-1}); Q(τ), the additional heating rate or cooling rate into the space, W.

$\rho c_p(t)$ and $k(t)$ are the functions of temperatures. ACH(τ) and Q(τ) are the functions of time. When I_{sum}, I_{win}, or I_{year} is zero, the indoor operating temperature lies completely within the thermal comfort zone.

The traditional approaches to reach thermal comfort are to adjust the four parameters to make *I* to be as low as possible (or even to approach 0). For the new approach reviewed in this paper, the process is just opposite: The ideal value or function of one of the four parameters (the other three parameters should be known) can be obtained by minimizing uncomfortable degree I_{sum}, I_{win}, and I_{year} value. There are two kinds of buildings. One is without any additional space heating or cooling system. For that case, Q = 0. However, it is often impossible to make I value to be 0. For this case, ideal parameters of ACH, k, and ρcp are the values or functions that can make I_{sum}, I_{win}, and I_{year} to be minimal. The other is that additional space heating or cooling is available, the ideal parameters for ACH, Q, k, and ρcp are those values or functions which can make I_{sum}, $I_{win,}$ or I_{year} to be zero. In other words, the ideal value or function of one of the four parameters can be obtained by solving the inverse problem.

It is noted that (1) Different from the traditional problem for analyzing the heating or cooling load of a given building (the thermophysical properties are known and are constant so that the relating equations describing the room temperature tend to be linear differential equations), the ideal $k(t)$ or $\rho c_p(t)$ or $Q(\tau)$ or $ACH(\tau)$ is unknown function and the relating equations of determining them are nonlinear differential equations; (2) a series of new concepts were put forward, i.e., ideal $ACH(\tau)$, $k(t)$, and $\rho c_p(t)$ for passive buildings (without any space heating or cooling) and ideal $k(t)$, $\rho c_p(t)$, $ACH(\tau)$, and $Q(\tau)$ for active buildings (with space heating or cooling). The buildings corresponding to the ideal parameters are called ideal passive energy efficient buildings and ideal active energy efficient buildings, respectively. After getting such ideal $ACH(\tau)$, $k(t)$, and $\rho c_p(t)$ for passive buildings and ideal ACH(τ), $k(t)$, $\rho c_p(t)$, and $Q(\tau)$ for active buildings, different persons can get guidance from them. For example, (1) researchers in building material science can know the best thermophysical properties for building envelope materials; (2) clients can know how to control natural ventilation; (3) the HVAC engineers can know how to operate space heating or cooling system.

1.2.4 Optimization Method

As an initial step, the approach for determining ideal $\rho c_p(t)$ function for a passive room was researched [9].

Objective: Minimize I_{sum} or I_{win};

Known: climate condition, indoor thermal source, building geometry, thermal comfort requirement;

Unknown: $\rho c_p(t)$;

Constraint conditions:

$$\int_{t_1}^{t_2} \rho c_{p,ex} dt = \rho H_{ex} = \text{constant} \tag{1.7}$$

$$\rho c_{p,ex}(t) \geq 0 \tag{1.8}$$

The N-segment method was put forward by Zeng et al. [9] to deal with this nonlinear optimization problem. The excessive volumetric specific heat is considered as a function of temperature. The ideal distribution of the excessive volumetric specific heat in effective temperature range with minimal I_{sum}, $I_{win,}$ or I_{year} can be determined through the sequential quadratic programming (SQP) method when other conditions are given.

The inverse problem approach also can be used in the measure and calculation of thermophysical properties, which is very important for simulation and evaluation of its energy-saving performance. The authors proposed a new method based on the inverse problem to deal with the measurements of thermal conductivity and specific heat of PCM-concrete brick during the phase change process.

The nonlinear optimization method can be used to determine these thermophysical properties. In this problem, the optimization objective and constraint can be described as follows [13]:

$$Min. \qquad \Delta c_p = \omega_1 |q_{mea} - q_{cal}| + \omega_2 |t_{mea} - t_{cal}| \tag{1.9}$$

$$s.t. \begin{cases} c_{p,low} \leq c_{p,i} \leq c_{p,high} \\ k_{p,low} \leq k_{p,i} \leq k_{p,high} \end{cases} \tag{1.10}$$

where the contributing factors (i.e., the relative weights) of errors of heat flux and temperature to the final errors of the thermophysical properties are as follows:

$$\omega_1 = \frac{\Delta\tau}{A\rho L |T_{n,\tau+1} - T_{n,\tau}|_{\min}} \tag{1.11}$$

$$\omega_2 = \frac{2q\Delta\tau}{A\rho L |T_{n,\tau+1} - T_{n,\tau}|_{\min}^2} \tag{1.12}$$

The optimization objective is the minimization of the difference between the calculated c_p and the real c_p distribution, which can be transformed into the weighted difference between measured and calculated heat flux and temperatures of various locations according to the error transfer function. The optimization constraints are the lower and upper limit of cp and k based on the measured materials.

The authors also compared the accuracy and time complexity of different optimization methods (Table 1.3). The results showed that the SQP method provided

Table 1.3 Accuracy and time complexity of different optimization methods [13]

Algorithms	RE_{flux} (%)	RE_{temp} (%)	Time complexity (s)
SQP	0.61	1.40	336
GA	0.64	1.42	3216
PSO	0.97	1.41	2816

the highest accuracy and least complexity compared with the particle swarm optimization (PSO) and genetic algorithm (GA) methods.

1.2.5 Optimal Thermal Properties

1. **Optimal constant thermal properties** [8]

Zhang et al. [8] used the inverse problem model to investigate the object building with constant physical properties in Beijing (Fig. 1.5). For the given case in Beijing, 50 MJ/(m^3 °C) was found to be the critical value of ρc_p for an ideal free-heating building in winter, and 100 MJ/(m^3 °C) was the critical value of ρc_p for an ideal free-cooling and ideal free-heating building for the whole year. However, according to the research, thermal physical properties of ordinary building envelope materials were linear with ρc_p in the range of 0–4.0 MJ/(m^3 °C), which were far less than what the ideal passive energy conservation building envelope required.

2. **Optimal $c_p(t)$**

By the nonlinear c_p function of temperature research, the best function of $\rho c_p(t)$ of building material for the internal thermal mass in summer in Beijing [9] is shown in Fig. 1.6. Figure 1.7 shows optimization results for the internal thermal mass for an entire year in Shanghai. For the cases studied, ideal specific heat of building wall is

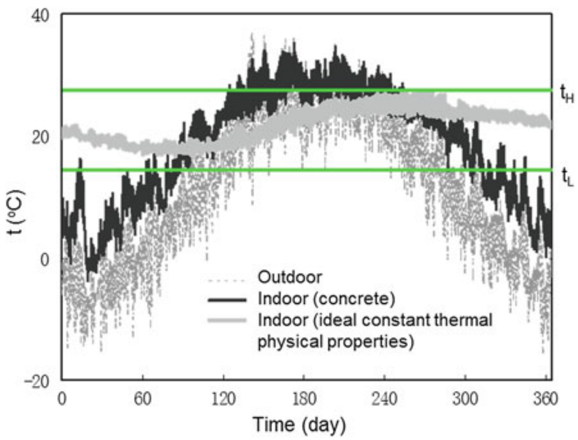

Fig. 1.5 The relationship of natural room temperature with different thermophysical properties [8]

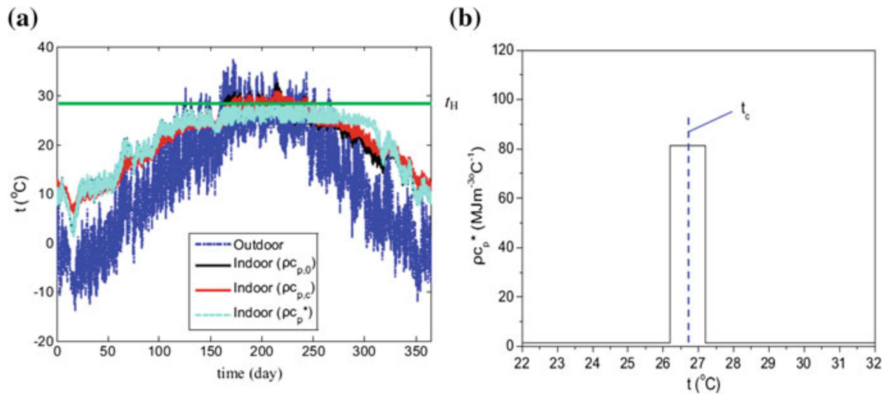

Fig. 1.6 Optimization results for the internal thermal mass in summer in Beijing (ρh_{ex} = 80 MJ m^{-3}) **a** t_{in} and **b** ρc_p*(t) [9]

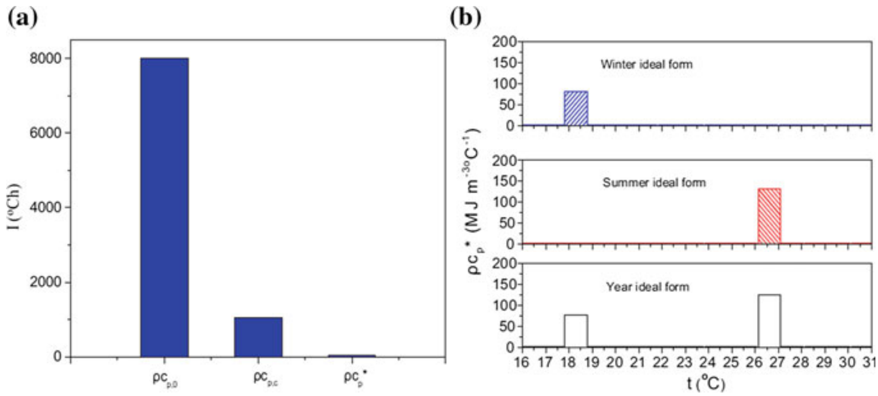

Fig. 1.7 Optimization results for the internal thermal mass for an entire year in Shanghai: **a** *I* and **b** ρc_p*(t) [9]

composed of basic value and ideal excessive value. The ideal form of excessive specific heat approaches to δ function [9, 10]. The research shows that the ideal ρc_p*(t) of the thermal mass for the whole year is close to the superposition of the ρc_p*(t) of the thermal mass in winter and that in summer. From Figs. 1.6 to 1.7, it is shown that the distribution of ρc_p(t) of building material is similar to PCM and give strong support for PCM building application.

Table 1.4 lists the critical optimal values of ρH_{ex} and their corresponding t_c of internal thermal mass for free-cooling and free-heating buildings for the study. From Table 1.3, it is shown that the critical values of ρH_{ex} are different under different climate, but the corresponding characteristic temperatures t_c of the ideal thermal mass are close to each other. They fall in the temperature ranges about 18.3–19.3 °C in winter and about 26.5–26.7 °C in summer in China.

Table 1.4 The critical values of ρH_{ex} and their corresponding t_c of internal thermal mass for free-cooling and free-heating building for the studied cities [9]

Regions		Winter		Summer	
		t_c (°C)	ρH_{add} (MJ m^{-3})	t_c (°C)	ρH_{add} (MJ m^{-3})
Harbin	▲	–	–	–	0
Urumchi	▲	–	–	26.7	60
Beijing	●	19.3	220	26.7	80
Shanghai	●	18.3	80	26.6	130
Lhasa	●	18.9	40	–	0
Kunming	●	–	0	–	0
Guangzhou	●	–	0	26.5	300

Note Filled Circle Thermal comfort can be met in a whole year; *Filled Triangle* Thermal comfort can be met in a summer; *Dash* Not exist/any

In Ref. [10], the authors applied the inverse method to the active room. The results showed that the additional heating and cooling energy consumption approach zero when the excessive enthalpy of the internal thermal mass was, respectively, higher than 30 and 300 MJ/m^3 for Beijing in winter and summer, and the corresponding characteristic temperatures were 18 and 26.3 °C. As for the internal thermal mass, thermal conductivity had little effect on the decreased heating (cooling) demand and the characteristic temperature due to optimization when its value was larger than 0.5 W/(m K) in both winter and summer. The optimized energy-saving quantity per unit of excessive enthalpy of internal thermal mass is higher than that of the external thermal mass in winter, whereas that of the external thermal mass is higher than that of the internal thermal mass in summer. The excessive enthalpy should be added in the internal thermal mass targeting both winter and summer performance in order to decrease the total amount of additional energy consumption.

In order to get the suitable thermal properties of phase change building envelope quickly, our research group also presented several analytical optimization methods. These analytical optimizations are also based on the above-mentioned inverse problem method. Xiao et al. [14] established a simplified theoretical model to optimize an interior PCM for energy storage in a lightweight passive solar room. For an optimal phase change temperature, the energy stored and released by the PCM should be equal in a cycle. The analytical optimization results showed that (1) the optimal phase change temperature depended on the average indoor air temperature and the radiation absorbed by the PCM panels; (2) the interior PCM had little effect on average indoor air temperature; and (3) the amplitude of the indoor air temperature fluctuation depended on the product of surface heat transfer coefficient and area of the PCM panels in a lightweight passive solar room.

Jiang et al. [15, 16] improved the Xiao's work, as they did not limit their analysis within one energy storage cycle and let the energy stored and released be the same.

They concluded that the optimal phase change temperature depends on the lower limit of indoor thermal comfort. It increased with air change rate, the overall heat transfer coefficient of the exterior wall and window, and decreased with increasing the lowest outdoor solar–air temperature at the outside surfaces of window and exterior wall, the lowest outdoor air temperature, and the inner heat source.

3. **Optimal k(t) and others**

Figure 1.8 shows the optimal thermal conductivity distribution of the external wall of the room located in Beijing approximates a square wave function. In this example, the lowest indoor operating temperature was increased by 2.5 °C and the highest indoor operating temperature was decreased by 2.2 °C over a whole year as compared with a traditional external wall (0.18 m reinforced concrete, ρc_p = 2.3 MJ/m^3 °C, k = 1.74 W/m °C, 0.07 m polystyrene board, ρc_p = 48.8 kJ/m^3 °C, k = 0.046 W/m °C). As a result, the integrated degree of discomfort was reduced by 64.3 % and the result has been validated to some extent [11].

Hua Jing et al. proposed a novel concept based on the inverse problem method to determine the optimal heating mode of residential rooms [17]. By minimizing the additive heating energy consumption and keeping indoor thermal comfort simultaneously, the optimal heating mode of residential rooms was determined by the variation method. In the simplest case, it was determined that the optimal heating method is air heating when air change hour (ACH) was low, and was wall heating when ACH was high. The results showed that ACH and thermal resistance of south wall had significant effect on the optimal heating method. In order to get the optimal heating method for a given building, a kind of discriminant was introduced, which could be described as the ratio of thermal resistance of the fresh air and south-facing wall.

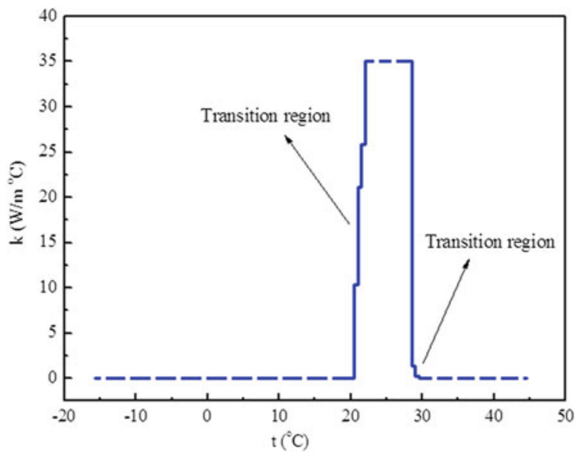

Fig. 1.8 Optimal k of external wall in Beijing [11]

1.3 Preparation and Properties of Shape-Stabilized Phase Change Materials (SSPCM)

According to the demand of applications in the energy-saving buildings, shape-stabilized phase change material (SSPCM) is a group of promising materials [18]. SSPCM should have proper phase change temperature, phase change latent heat as high as possible, and proper heat transfer rate. SSPCMs are also required to have enough strength to maintain the shape, to have good durability and long lifetime, and to be nonflammable for safety. Therefore, many researches were carried out to achieve these targets.

Paraffin-based SSPCM is the most concerned and is generally prepared by melt-blending paraffin with various polymer matrices. Owing to the similarity of the chemical structure and thus the affinity to paraffin, polyethylene (PE) is the most often used polymer matrix of SSPCM [19–22]. Inaba et al. [19] first reported a SSPCM made of high-density polyethylene (HDPE) and paraffin. Apart from PE, other polymer matrices such as polypropylene (PP) [23, 24], styrene–butadiene–styrene block copolymer (SBS) [25], ethylene–propylene–diene copolymer (EPDM) [26], ethylene–octene copolymer (POE) [27], and ethylene–vinyl acetate copolymer (EVA) [28] were also used. Other PCMs were rarely used in SSPCM.

1.3.1 Preparation of SSPCM

In order to obtain good, balanced processability, mechanical property, and encapsulation of SSPCM, there are some criteria for polymer matrices:

- Polymer matrix has good compatibility with PCMs;
- For the convenience of processing, the difference of melting temperature between the PCM and the matrix is small so that they are easy to be blended and the evaporation of paraffin is suppressed mostly;
- For the application safety, the difference of melting temperature between the PCM and the matrix is large enough to ensure the shape and the strength when PCM is melted.

PE has good compatibility with paraffin. Its melting temperature is only about 140 °C. It is strong and tough. These features make it the most often used. However, its high crystallinity brings negative effect to the encapsulation. By using elastomers with high paraffin-absorbing ability as well, good processability and encapsulation can be achieved at the same time [29]. Figure 1.9 shows the paraffin-absorbing curves of some elastomers including EPDM, SBS with different S/B ratios, and styrene–isoprene–styrene block copolymer (SIS). All these elastomers exhibited good paraffin absorption ability.

Since the melt viscosities and melting temperatures of paraffin, PE, and elastomers differ greatly, the two-screw extruder/mixer with strong shearing torque was

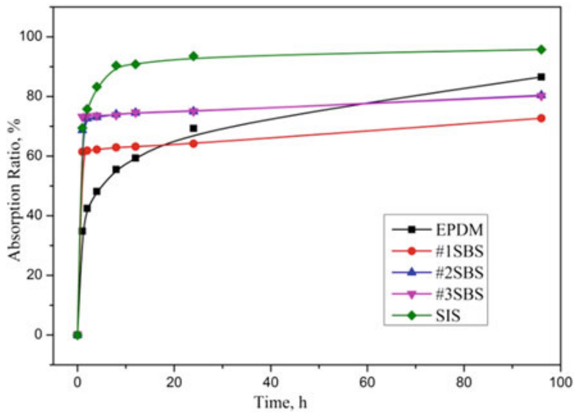

Fig. 1.9 Paraffin-absorbing curves of various elastomers with time [29]

required to achieve homogeneous distribution of paraffin in the matrix. With proper compositions, the prepared SSPCMs could be easily extruded, without paraffin migration to the surface. Figure 1.10 shows the microscopic morphology of HDPE/SBS/paraffin in which paraffin was etched by ethanol in order to show the matrix structure. Obviously, the matrix formed a network structure and paraffin dispersed homogeneously in it.

In order to improve the mechanical strength of SSPCMs, cross-linking of the matrix was carried out. Proper amount of dicumyl peroxide (DCP) was added during the melt blending, and the tensile strength was increased significantly, as shown in Fig. 1.11. At the same time, the proper cross-linking did not worsen or even improve the cyclic stability [30].

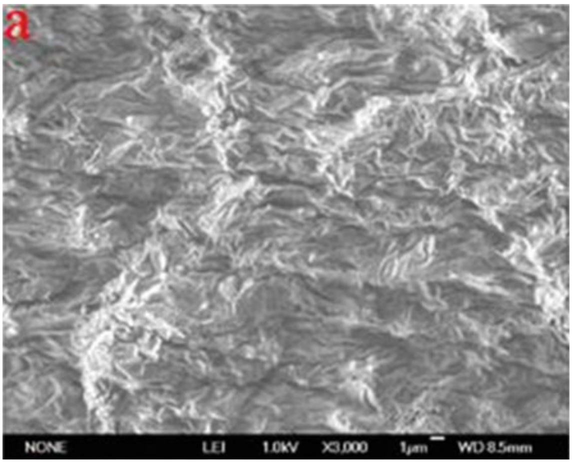

Fig. 1.10 Microscopic morphology of HDPE/SBS/paraffin system (paraffin was etched by ethanol to show the matrix structure)

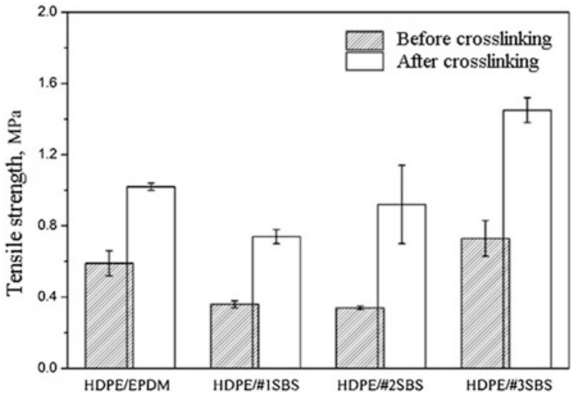

Fig. 1.11 Tensile strength of SSPCMs before and after cross-linking

1.3.2 Thermal Property

Paraffin with phase change temperature of 20–30 °C is required for SSPCM in energy-saving buildings. From practical applications' point of view, people expect the phase change enthalpy as high as possible which means as much paraffin as possible. However, since polymer matrix is needed for the shape and strength, the optimal paraffin concentration is generally 50–70 %. Figure 1.12 shows DSC curves of three paraffins (the detail information is listed in Table 1.5) and SSPCMs based on paraffin #1. The melting temperatures of SSPCMs are about 21 °C, and the melting enthalpies are about 100 kJ/kg. Owing to the blend nature, there is no reaction or strong interaction between paraffin and the matrix, so SSPCMs exhibit the same phase change temperature as paraffin in it. Neglecting the evaporation loss of paraffin during processing, the phase change enthalpy of SSPCMs is equal to that contributed by paraffin in it.

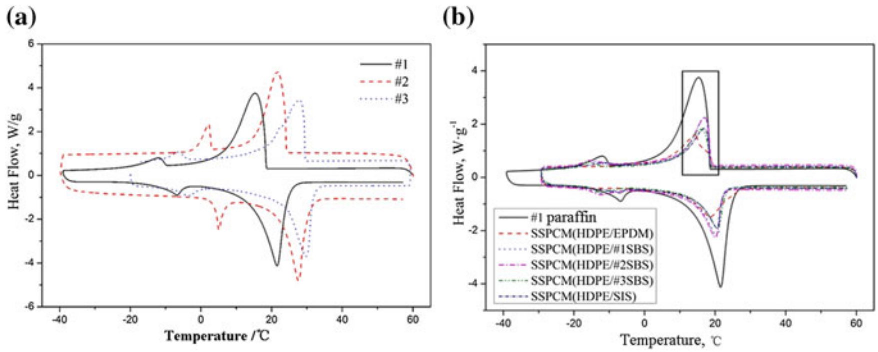

Fig. 1.12 DSC curves of three paraffins (**a**) and SSPCMs based on paraffin #1 (**b**)

Table 1.5 Thermophysical parameters of three paraffins

Paraffin	Solid–liquid phase change temperature/°C		Phase change enthalpy/J/g		
	Melting	Freezing	Melting	Freezing	Average
#1	21.6	15.4	189.2	188.6	188.9
#2	27.6	21.6	175.0	179.9	177.5
#3	29.7	27.4	165.4	167.2	166.3

1.3.3 Cyclic Stability

Previous research demonstrated that organic PCMs had perfect chemical stability. After thousands of heating/cooling cycles in DSC crucibles, the phase change temperatures and enthalpies of organic acids and paraffins remained nearly unchanged [23, 31–33]. However, under practical circumstances, PCM would migrate and evaporate from the matrix and the thermal energy storage capacity decreased consequently.

By testing the cyclic stability of SSPCMs under the condition that simulating real circumstances, the property deterioration could be determined. Luo et al. [27] tested the stability of three paraffin-based SSPCMs by repeating heating samples at 60 °C for 1 h and cooling samples at room temperature for 0.5 h. The mass loss after each cycle was measured. They found that POE and EVA were better for encapsulating paraffin and the mass losses of POE/paraffin and EVA/paraffin were much lower than that of HDPE/paraffin. Wang et al. [29] also demonstrated the much better cyclic stability of HDPE/elastomer/paraffin than HDPE/paraffin. The mass loss of the former after 100 cycles was only 8–10 %, while the mass loss of the latter after 40 cycles reached 13.6 %, as shown in Fig. 1.13.

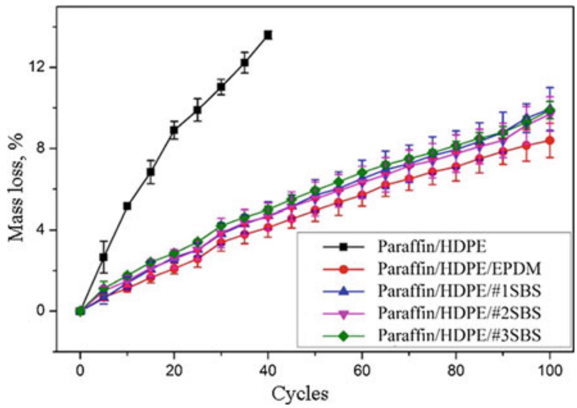

Fig. 1.13 Mass loss of various SSPCMs after heating/cooling cycles [29]

1.3.4 Thermal Conductivity

SSPCMs have poor thermal conduction property, and the thermal conductivity is only about 0.2 W/m K. According to the simulation result by Xu et al. [34], for SSPCMs in passive solar buildings, improving the thermal conductivity helped to increase the solar energy absorbing speed. Inorganic fillers with high thermal conductivity were often added to improve the thermal conductivity of SSPCMs [35]. Among them, carbon fillers [25, 36], e.g., expanded graphite (EG) and carbon nanotube (CNT), were the most widely used.

The thermal conductivity of SSPCM, λ, can be calculated by the following equation:

$$\lambda(T) = \alpha(T) \times Cp(T) \times \rho(T) \tag{13}$$

where α, $C_{p,}$ and ρ are thermal diffusivity (m^2/s), specific heat (J/(kg K)), and density (kg/m^3) of SSPCM.

EG and CNT are effective to increase the thermal diffusivity of SSPCM. C_p depends on the status of paraffin and is the function of the temperature. Generally, thermal conductivity is determined in solid state or liquid state of paraffin at which C_p is nearly constant.

EG was prepared by thermal treatment of expandable graphite at high temperatures. The so-formed porous structure (in Fig. 1.14) can absorb paraffin by capillary force and Van de Waals force. EG dispersed in SSPCMs helped the thermal conduction greatly. In contrast, graphite particles (GP) exhibited much less improvement to the thermal conductivity of SSPCM, as shown in Fig. 1.15.

CNT is also an effective filler for thermal conduction improvement owing to its large aspect ratio (in Fig. 1.14). When it is dispersed in SSPCM well, it may form a bridge connection structure and increase the thermal conductivity with low concentration. But CNT is quite easy to aggregate, so how to disperse it homogeneously in SSPCM is a great challenge.

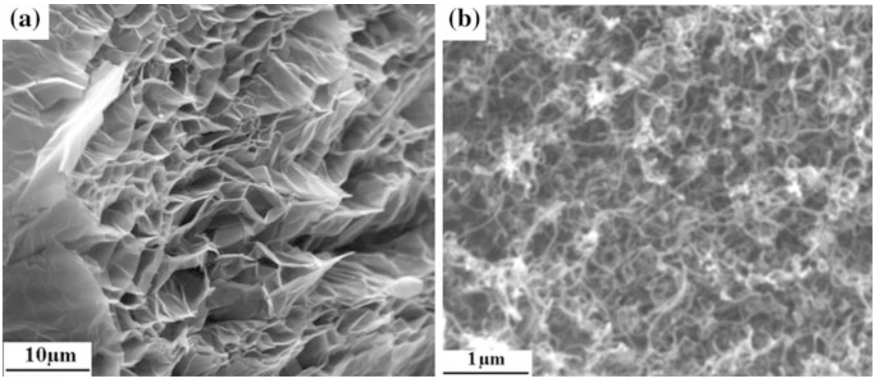

Fig. 1.14 Morphology of EG (**a**) and CNT (**b**)

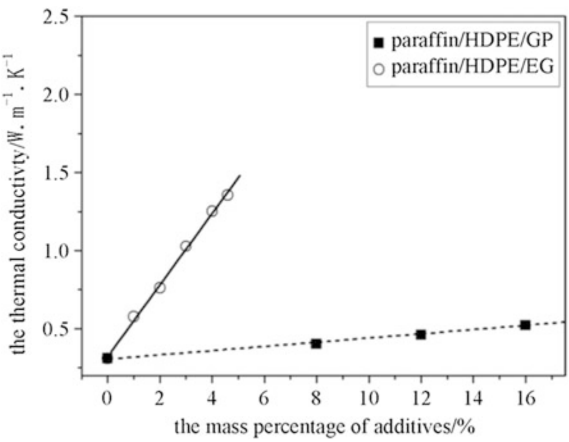

Fig. 1.15 Thermal conductivity of SSPCM with EG and GP, respectively [36]

There is a synergistic effect between EG and CNT. EG platelets dispersed well in SSPCM, and CNT connected EG platelets to form a bridge, so a connection structure for thermal conduction was formed, as shown in Fig. 1.16. However, there were still aggregations of CNT in SSPCM. This aggregation weakened the thermal conduction improvement. Much higher thermal conductivity is expected when CNT dispersed well in SSPCM. This still needs further work.

1.3.5 Flame Retardance

In SSPCMs, both paraffin and polymer matrices are flammable in the air, which takes great danger and almost disables its possible wide utilization in buildings.

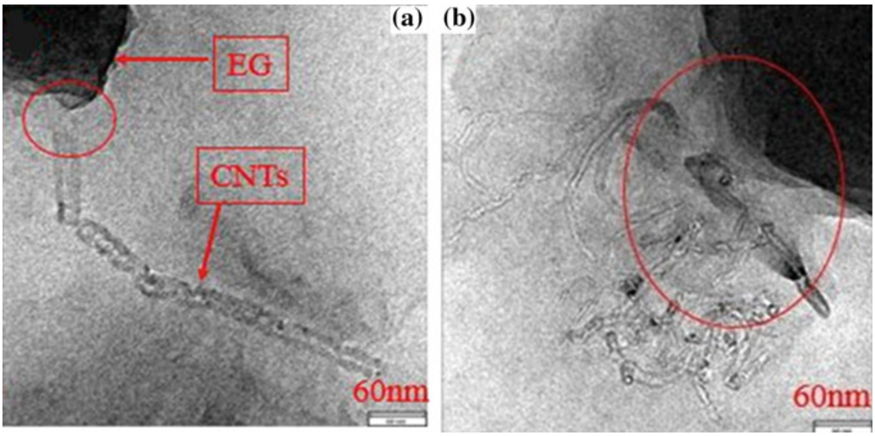

Fig. 1.16 Microscopic morphology of SSPCMs with hybrid $EG_{2\%}MWCNT_x$ filler. **a** Bridge connection between EG platelets and MWCNTs; **b** aggregation of MWCNTs

Therefore, flame retardance of SSPCMs attracted great attentions. Generally, inorganic fillers, such as montmorillonite (MMT) and EG, and intumescent flame retardants (IFRs), such as pentaerythritol (PER), melamine polyphosphate (MPP), and ammonia phosphate (APP), were added to improve the flame resistance of SSPCMs [27–40].

However, owing to the low melting/boiling temperature and relatively high vapor pressure, paraffin for energy-saving buildings contributed more combustible gas at low temperatures and led to much higher flammable risk. Conventional IFRs acted at higher temperature than the boiling temperature of paraffin. Therefore, how to hinder the evaporation of paraffin at high temperature is the key issue for flame retardance of SSPCM.

SSPCM is easy to burn. The combustion time is only 20 s. By melt-blending EG treated at various temperatures, the combustion time was increased by 4–5 times, as shown in Fig. 1.17 [41]. EG treated at various temperatures had different porous structure and thus strong absorption ability to paraffin. This helped to hinder the evaporation of paraffin and prolonged the combustion time. MMT is another effective inorganic flame retardant for SSPCM. The layered structure helped to maintain paraffin between layers and decrease the combustible materials. MMT also prevented oxygen from penetrating into SSPCM. With cross-linking agent, the thermal stability of the polymer matrix increased so that it was not easy to decompose to combustible materials. So the combustion time prolonged further, as shown in Fig. 1.18.

With EG, MMT, and/or cross-linking agent, the heat release rate was decreased by up to 72.7 % from that of SSPCM. In addition, formation of CO_2 and CO decreased significantly, and the large amount of residue (up to 27.8 %) formed [41].

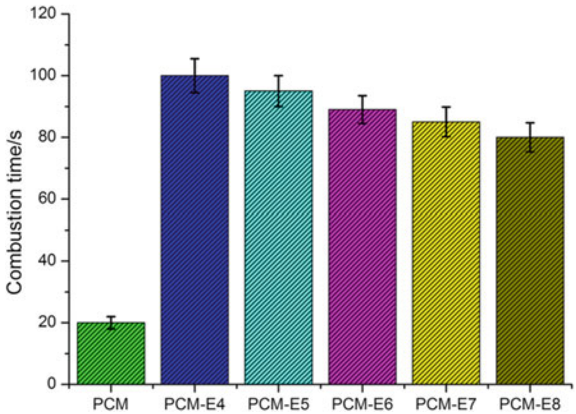

Fig. 1.17 Combustion times of SSPCMs with EG treated at various temperatures [41] (*-E4 ~ *-E8 means EG was treated at 400–800 °C)

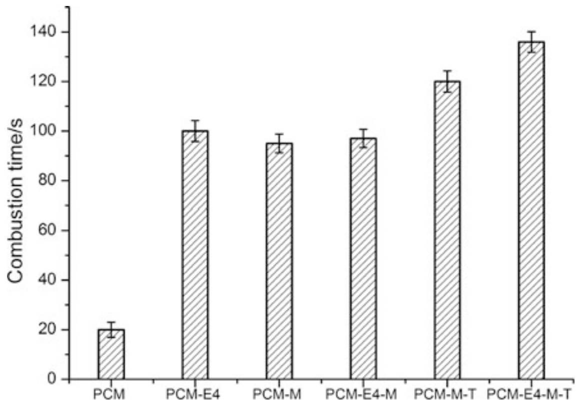

Fig. 1.18 Combustion times of SSPCMs with EG, MMT, and cross-linking agent [41] (*-E4, *-M, *-E4-M, *-M-T, and *-E4-M-T means SSPCMs with EG, with MMT, with EG and MMT, with MMT and cross-linking agent, and with EG, MMT, and cross-linking agent)

1.4 Future Research

Research on the inverse problem for PCMs and application in building envelop including the preparation of SSPCM by our group is reviewed, which is very different from the conventional approaches and can be used to guide the building envelope thermal performance design and material preparation and selection. However, it needs further research on the following problems:

- This paper focuses only on the research of the thermal properties of building envelope material. However, the optimal structures of building envelope need further research based on the inverse problem in order to make full use of renewable energy.
- High performance and low cost of SSPCM, which can be used as building envelope material, needs more development.
- Research on experiments and practical application is needed to test the real effects in different climates.

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Chapter 2
Natural Composite Membranes for Water Remediation: Toward a Sustainable Tomorrow

Noor Hana Hanif Abu Bakar and Wei Leng Tan

Abstract Natural composites as green membranes have shown great potential in water remediation. These membranes combine merits from both natural polymer and inorganic or organic additives. Natural polymers are biodegradable, non-toxic and offer flexibility for design purposes. Incorporation of additives can enhance the mechanical and thermal properties or impart antibacterial and catalytic properties to the composite. This chapter provides an overview of the different types of natural polymer composite membranes and their functions. It also highlights the recent development of cellulose, chitosan, and natural rubber composite-based membranes in water treatment technologies between 2010 and 2015.

Keywords Natural polymer · Membrane · Composite · Additive · Water treatment

2.1 Introduction

The global population has increased from 5.3 billion in 1990 to 7.3 billion in 2015 [1]. With this increase, there has been a race toward rapid industrialization to provide a so-called better quality of living. Sadly, this has caused a rise in both air and water pollution. Numerous measures have been taken to curb the extent of toxic waste especially in water resources, as water is one of the fundamental essentials in our everyday life. Although the numbers have decreased over the years, 663 million people worldwide still lack improved drinking water resources, while 159 million people still use surface water [1].

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In recent years, the development of membrane technology has geared up as a means to overcome water pollution effectively. Statistics show that membrane technologies contribute up to 53 % of the total world processes for clean water production [2]. The increasing demand in membrane technology is mainly due to their features itself as well as the ability to apply them in sustainable industrial designs. Ideally, membranes should have characteristics such as increased life span, good mechanical, thermal, and chemical stability, low cost, and minimum maintenance. The use of membranes also enables the improvement of industrial design whereby less land space is required for the setting up of various processes, energy consumption is low, and no additional chemical is needed when compared to conventional technologies. This renders membranes as an economical technology with potential in various fields such as separation, filtration, and catalysis for water treatment.

Membranes have been used for water treatment for more than 45 years. A wide range of materials are available for the fabrication of membranes. These materials can generally be grouped into ceramic-based and polymeric-based membranes. Ceramic-based membranes are popular as they are thermally and chemically more stable, have high porosity, and have a longer life span. Even so, they are also more expensive and brittle. Polymer-based membranes on the other hand offer flexibility in design, are cheaper, and can remove dissolved ions and organics more efficiently [3]. Nevertheless, they also have some disadvantages including high hydrophobicity, exposure to biofouling, low fluxes, and low mechanical strength. We realize that there is an abundance of literatures on both ceramic- and polymeric-based membranes [4–8]. Particularly, recent reviews on polymer nanocomposites for membrane applications have emerged [9, 10]. The majority of these reviews are focused on synthetic polymers. Hardly any reviews related to natural polymer composite membranes can be found in the literature [11]. As such, this chapter has been organized to give the readers an overview of the different types of natural polymer composite membranes and their functions. This chapter highlights the application of interesting cellulose-, chitosan-, and natural rubber-based composite membranes in sustainable technologies between 2010 and 2015.

2.2 Natural Composite Membranes

The interest in natural polymers has escalated in recent years as these materials are biodegradable and non-toxic. It is an alternative to petroleum-based polymers which, although has widespread application, has depleted drastically while causing severe environmental and health problems. According to John and Thomas [12], natural polymers can be categorized into two main classes. These are polymers which are readily available in living organisms as well as those which originate from renewable resources but have to be polymerized. The earlier type includes cellulose and protein, while examples of the later are lactic acids and triglycerides. As membranes, polymers such as cellulose, chitin, and chitosan are commonly used. However, other polymers such as gum and alginate have also attracted interest. Mostly, these polymers are rarely used solely. The main reason being that by itself, these polymers are unable to meet the specific requirements required to fabricate effective membranes. For instance, pure chitin is brittle, has low porosity, and low chemical affinity [13]. Cellulose is more widely used as membranes. The suitability of this natural polymer for membrane applications lies in the fact that they are cost-effective, hydrophilic, semipermeable, porous, offer good transport characteristics, and has film-forming ability. Even so, cellulose membranes also suffer from poor chemical and thermal resistances and lack an abundance of reactive functional groups, inferior mechanical strength, lower fluxes, and fouling issues. Throughout the years, there have been continued efforts to improve natural-based membranes' performance from different aspects—material modifications, material processing, and module's design. In terms of material modifications, the various shortcomings of these renewable polymers can be addressed by (1) combining a polymer or inorganic layer with a natural polymer or (2) incorporating an inorganic/organic additive into the natural polymer. Such modifications of the polymers for membrane technology are critical in order to develop high-performance membranes. Considering the nature of natural composite membranes, we define natural composite membrane as a physical barrier primarily made from green materials that create an interface for mass transfer and/or reactions between two phases. It can be inert or catalytically active depending on its composition.

Modification of natural polymers by combination with another polymer is one of the most popular methods for the preparation of natural membranes. Polymer blending between a synthetic polymer and a natural polymer has frequently been investigated. Prakash et al. [14] highlighted the use of chitosan and nylon 6 blends as membranes for the removal of copper and cadmium ions from synthetic wastewater. In contrast, El-Gendi et al. [15] used blends of these polymers for water desalting purposes. However, as a route toward sustainable technologies, the development of membranes composed of only blended natural polymers, such as natural rubber and chitosan [16], chitin and cellulose [13] or N, O-carboxymethyl chitosan and cellulose [17], has been reported. Blending chitin with cellulose is advantageous for adsorption of heavy metals as it combines the porosity and chemical affinity of cellulose with the excellent binding forces of chitin toward heavy metals. The polymers complement each other resulting in a porous membrane with better uptake capacity of heavy metals due to the availability of acetyl groups from chitin [13].

Grafting is another alternative to alter the properties of a polymer with another. This method allows the introduction of new functional groups which among other purposes can inhibit dissolution of a hydrophilic polymer during the treatment process and additionally increase the number of adsorption sites [18]. An interesting method to graft chitosan to another polymer was presented by Mansourpanah and coworkers. In their work, polyethersulfone (PES) membranes coated with chitosan-grafted acrylamide were developed using a microwave as the grafting agent [19]. The microwave generates radicals at O and N atoms by breaking the bonds of O–H and N–H of chitosan. This then leads to grafting or graft polymerization.

Addition of inorganic/organic additives into natural polymers has received less attention when compared to modification via polymer–polymer blending or grafting. Generally, natural polymer composites are a material formed through a combination of polymer as the continuous phase (called the matrix) and additive which makes the dispersed phase. It can also be defined as a multilayer or combination of organic and inorganic phases. The combination of polymer and additive affords a multifunctional material which adopts properties of the respective constituents. When discussing natural polymer composites, the natural polymer can act as either or both the matrix or dispersed phase. An example is the incorporation of nanochitin whiskers (NCW) in poly(vinylidene fluoride) (PVDF) membranes. The NCW improve not only the mechanical strength of the membrane but also the water permeability and antifouling properties [20]. Addition of the NCW enhances the hydrophilicity properties of PVDF which is originally hydrophobic. Another work which discusses the function of natural polymer as dispersed phase is found elsewhere [21]. Further discussions highlighting the use of natural polymers as the matrix for the formation of membranes are presented in the following sections. A summary of various inorganic–organic membranes reported between 2010 and 2015 is presented in Table 2.1.

2.3 Types and Shapes of Natural Composite Membranes

Natural composite membranes can be divided into two major groups, which are organic—organic and inorganic—organic membranes, as in Fig. 2.1. Various types of membranes can be obtained depending on the fabrication techniques employed. As such, organic–organic membranes can further be segmented according to thin-film composites and blends. This is shown in Fig. 2.2a, b, respectively. Thin-film composites refer to membranes that have a bi- or multilayer structure. In contrast, membranes formed from polymer blends have monolayer structures. Both the thin-film and blend composites can be achieved by chemical or physical means. Blend membranes were formed by Almaria and coworkers from poly(vinyl alcohol) (PVA) and sago starch. The blend was cast in a monolayer form and used for the recovery of ethyl acetate from water [90]. Thin-film composites may be composed of several layers, formed from a combination of seperate polymers, grafted polymers and/or polymer blends. The blends include reactive and non-reactive polymers. Chen et al. [91] described the fabrication of a thin-film polymer composite via grafting whereby polyacrylonitrile (PAN) was grafted to cellulose acetate to form the so-called layers. In contrast, the thin-film composites can be accomplished

Table 2.1 Summary of natural polymer composite membranes

Natural polymer matrix	Additives	Type	Function	Application	Refs.
Chitosan	Clay	TFC	Filtration	Removal of Hg(II) and As(III)	[22]
	TiO_2/glass plates	TFC	Adsorption/catalysis	Removal of Reactive Red 4 dye	[23]
	Mesoporous carbon particles	MM	Adsorption	Adsorption of fuchsin dye	[24]
	Fe_3O_4 NPs	MM	Catalysis	Degradation of RB 19 dye	[25]
	Cobalt phthalocyanine	TFC	Catalysis	Degradation of rhodamine B	[26]
	MMT	MM	Adsorption/filtration	Removal of Bezaktiv Orange V-3R dye	[27]
Chitosan/PVA	Laccase-MWCNT	MM	Catalysis	Degradation of diclofenac	[28]
	Laccase	MM	Catalysis	Removal of 2, 4-dichlorophenol	[29]
	NH_2-functionalized MWCNT	MM	Adsorption	Removal of Cu(II)	[30]
Chitosan/gum arabic	CNT	MM	Adsorption	Removal of total dissolved solids	[31]
Chitosan/cellulose	Ag NPs	MM	Antimicrobial	Anti-biofouling	[32]
	Polyacrylic acid–Ag NPs	MM	Antimicrobial	Anti-biofouling	[33]
	Dithizone	TFC	Adsorption	Adsorption of lead	[34]
	5,10,15,20-Tetrakis (1-methyl-4-pyridinio) porphyrin tetra (p-toluenesulfonate)	TFC	Adsorption	Removal of cadmium	[35]

(continued)

Table 2.1 (continued)

Natural polymer matrix	Additives	Type	Function	Application	Refs.
Chitosan/polyacrylonitrile	Amine-Fe_3O_4	MM	Adsorption	Removal of humic acid	[36]
Chitosan/polyethersulfone	Fe_3O_4	MM	Filtration/antimicrobial	Removal of Direct Red 16 dye	[37]
Chitosan/polyamide	Graphene oxide	TFC	Antimicrobial	Antifouling	[38]
Cellulose	CuO NPs	MM	Antimicrobial	Disinfection of water	[39]
	TiO_2 nanothorn	TFC	Filtration/catalysis	Removal of MB and humic acid	[40]
	Dendrimer–Ag	MM	Catalysis/antimicrobial	Removal of rhodamine B/disinfection of water	[41]
Oxidized cellulose	Cu NPs	MM	Catalysis	Degradation of p-nitrophenol	[42]
Regenerated cellulose	TiO_2	MM	Catalysis	Degradation of phenol	[43]
	Quaternary ammonium salt, amino alkyl		Antimicrobial/filtration	Anti-biofouling	[44]
Regenerated cellulose/polydopamine	SiO_2	MI	Adsorption/filtration	Removal of artemisinin	[45]
Cellulose/PVC	Fe_3O_4 NPs	MM	Adsorption/filtration	Removal of lead	[46]
Cellulose acetate	SDS	TFC	Filtration	Rejection of pesticides	[47]
	L-dopa	TFC	Filtration	Antifouling	[48]
	POSS NPs	MM	Filtration	Salt rejection	[49]
	Alkyl derivative of resorcinarene	PI	Adsorption/filtration	Removal of Pb(II), Cd(II), and Zn(II)	[50]
	Iron NPs	MM	Filtration	Rejection of phosphates and organic pollutants	[51]

(continued)

Table 2.1 (continued)

Natural polymer matrix	Additives	Type	Function	Application	Refs.
	TiO_2	TFC	Filtration	Separation of chlorine and turbidity	[52]
	MWCNTs	MM	Filtration	Salt rejection	[53]
	Resorcinarene derivatives	PI	Filtration	Separation of Zn(II) and Cd(II)	[54]
	Ag NPs	MM	Filtration	Anti-biofouling	[55]
	MSG	MM	Filtration	Rejection of solute	[56]
	ZnO	TFC	Antimicrobial/adsorption	Salt rejection, anti-biofouling	[57]
	SPEEK-bentonite	TFC	Filtration	Daily wastewater treatment	[58]
	Modified coal	MM	Filtration	Separation of solute	[59]
	(BMIM)Cl	MI	Filtration/adsorption	Removal of salicylic acid	[60]
	CNT	MM	Filtration	Salt rejection	[61]
	Organo-MMT	MM	Filtration	Removal of humic acid	[62]
	TiO_2/ZnO	TFC	Filtration/catalysis/antimicrobial	Removal of humic acid/antifouling	[63]
	ZnO	MM	Catalysis	Degradation of rhodamine B	[64]
	Ag/TiO_2, Au/TiO_2	MM	Catalysis	Degradation of MB	[65]
	TiO_2/carbon	MM	Catalysis	Degradation of MO	[66]
	$SrTiO_3$/TiO_2	TFC	Filtration/catalysis	Removal of acid orange 7	[67]

(continued)

Table 2.1 (continued)

Natural polymer matrix	Additives	Type	Function	Application	Refs.
	TiO_2/ZnO	MM	Catalysis	Degradation of rhodamine B	[68]
NH_2-functionalized cellulose acetate	SiO_2 NPs	MM	Adsorption	Removal of Cr(VI) ions	[69]
Cellulose acetate/PEG-600	Ag	MM	Antimicrobial	Salt rejection/anti-biofouling	[70]
Cellulose acetate/PAN	Ag NPs	TFC	Filtration/antimicrobial	Salt rejection/anti-biofouling	[71]
Cellulose acetate/PANI	Phytic acid	MM	Adsorbent	Removal of Hg(II) and Cr(VI)	[72]
Cellulose acetate/PEG	SiO_2	MM	Filtration	Salt rejection	[73]
Cellulose acetate/polyethersulfone	Bentonite	MM	Filtration	Car wash effluent treatment	[74]
Cellulose acetate/cellulose triacetate	Boehmite	MM	Filtration	Salt rejection	[75]
Cellulose triacetate	Modified ZnO	MM	Filtration	Separation of rhodamine B	[76]
	Aliquat 336	PI	Adsorption	Separation of acid violet 90 and acid yellow 127	[77]
	Cyphos	PI	Filtration/adsorption	Separation of Zn(II)	[78]
	Activated carbon (AC)	MM	Adsorption/filtration	Removal of uranium	[79]
	2-(10-carboxydecylsulfanyl) benzoic acid methyl monoester	PI	Filtration	Separation of Pb(II)	[80]
	Cyanex 923	PI	Adsorption/filtration	Removal of phenol	[81]

(continued)

Table 2.1 (continued)

Natural polymer matrix	Additives	Type	Function	Application	Refs.
	AC	MM	Filtration/adsorption	Removal of arsenic	[82]
	Iron-doped AC	MM	Filtration/adsorption	Removal of uranium	[83]
Carboxymethyl cellulase/polyelectrolyte complex	SiO_2	MM	Adsorption	Separation of isopropanol	[84]
Hydroxyl ethyl cellulose/sodium alginate	Humic acid	MM	Adsorption	Adsorption of Cd(II)	[85]
	Humic acid	MM	Adsorption	Removal of MB and rhodamine B	[86]
Nitrocellulose	Polyvinyl-N-carbazole-CNTs	TFC	Antimicrobial	Anti-biofouling	[87]
ENR	Fe_3O_4	MM	Adsorption	Removal of oil	[88]
ENR/PVC	TiO_2	TFC	Catalysis	Degradation of MB	[89]

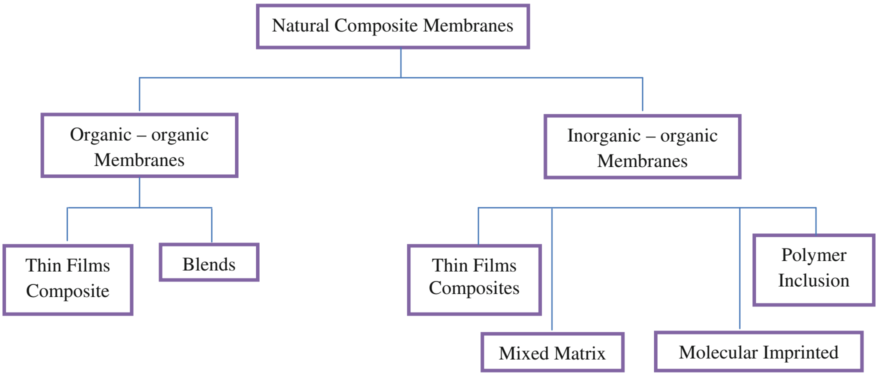

Fig. 2.1 The types of natural composite membranes

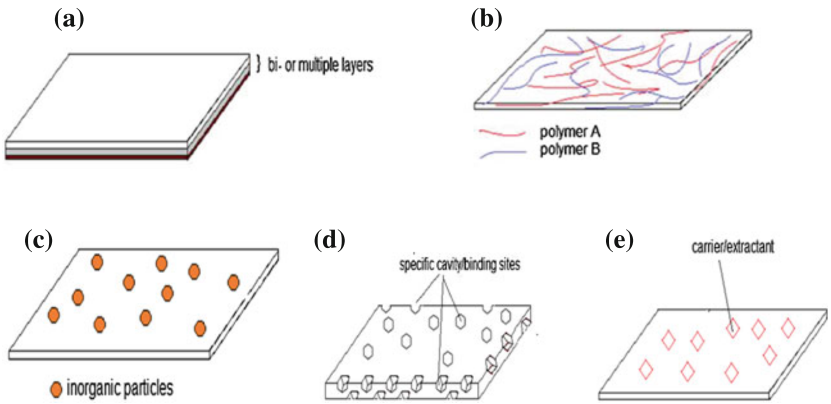

Fig. 2.2 Structures of various natural composite membranes: **a** thin-film composites, **b** blends, **c** mixed matrix, **d** molecular imprinted, and **e** polymer inclusion

physically by simple casting or spin coating techniques. An example of these kinds of membranes is the combination of a PAN layer which acts as a support with a cross-linked cellulose layer on top [92].

In contrast to organic–organic membranes, there exist four types of inorganic–organic membranes. In this case, the bi- or multilayer thin-film composites can be composed of layers of inorganic and organic materials. These arrangements can be fabricated by simple casting, spin coating, or impregnation/dip-coating technique. Thin-film composite membranes of ceramic and cellulose acetate layers were prepared using dip-coating technique [93]. Another example is the fabrication of a layer of PAN followed by a film of cellulose acetate with silver nanoparticles on top. The layer of silver nanoparticles functions as an antibacterial agent for antifouling purposes, while CA plays the role of a stabilizer to control the dispersion and growth of the Ag particles. The PAN on the other hand acts as a filter for water. This shows that in this type of membrane, each layer has a specific role [71].

The mixed matrix membrane differs from thin-film composite in terms of, only one layer exists and it is usually composed of inorganic particles dispersed throughout a natural polymer matrix. Inorganic particles generally carry the role of improving certain properties of the polymer matrix. For instance, the water permeation and thermal stability of the cellulose acetate membrane can be greatly enhanced by incorporating TiO_2 nanoparticles [94].

Polymer inclusion membrane is also known as a liquid membrane. Generally, it consists of a polymer, plasticizer, and carrier. The most frequently used natural polymer for the formation of these membranes is cellulose triacetate. This is attributed to their characteristic which demonstrates good stability [95]. The carrier plays the most significant role in these types of membranes, as it facilitates the transport of matter for separation. Mainly, when natural polymers are employed, it has been applied for the separation of heavy metal ions [54, 78, 80]. However, some works have reported the use of this kind of natural membrane for the extraction or organic molecules such as phenol [81] and acid dyes [77].

Molecular imprinted membranes are natural polymers with additives (inorganic fillers, functional monomers, and ionic liquids [60]) designed to target specific substances. In other words, this type of membrane is tailor-made for the treatment of particular molecules in wastewater. Basically, the membranes are formed by polymerizing the polymer in the presence of a template. Upon formation, the templates are removed. These molecular imprinted membranes can stand-alone; however, inorganic fillers can add value to the membranes. For example, in the absence of inorganic filler such as TiO_2, a calcium alginate-based molecular imprinted membrane is capable of removing methyl orange dye physically [96]. Even so, addition of TiO_2 improves the functionality of this membrane by allowing adsorption followed by the degradation of the methyl orange dye [97]. Other works have been conducted using SiO_2 as filler in cellulose-based molecular imprinted membranes. In this case, the SiO_2 imparts better mechanical strength to the membrane [45].

Natural polymer composite membranes are generally fabricated into three shapes: flat sheet, hollow fiber, and nanofibrous. These are shown in Fig. 2.3a–c. Flat sheet membranes are easily prepared, and the permeating substances can be extracted by using gravity flow without the aid of high-pressure technologies [98]. As compared to flat sheet membranes, both hollow fiber and nanofibrous membranes exert higher surface area per volume, making them more efficient adsorbents, filters, or catalysts. Hollow fiber membranes also enable very compact and high-packing-density systems which consume a small floor place. On the other hand, nanofibrous membranes have advantages of high porosity and charge density, good mechanical strength, and high flux permeability [99, 100].

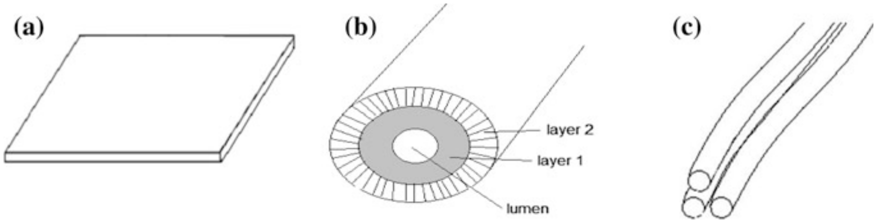

Fig. 2.3 Various shapes of natural composite membranes: **a** flat sheet, **b** hallow fiber, and **c** nanofibrous

2.4 Main Functions and Characteristics of Natural Composite Membranes

As natural polymer composite membranes can be either inert or catalytically active, the role of these membranes can be categorized based on the following areas:

(i) Filtration
This process can be further classified according to the pore size of the filter. This includes microfiltration, ultrafiltration, nanofiltration, and reverse and forward osmosis. A detailed summary on the various classes, their respective pore sizes, and the materials these filters are capable of removing has been given elsewhere [101].

(ii) Adsorption
This process involves the capture of substances by physical or chemical means. Physisorption is a reversible reaction that allows substance recovery possible, while the latter is not. Adsorption has been extensively applied for the removal of multivalent heavy metal ions, for example, Pb (II), Cd (II), and Cr (IV) [34, 35, 69]. Organic substances such as phenol, dyes, and artemisinin can also be removed and recovered by using molecular imprinted membranes with high selectivity.

(iv) Catalysis
In these membranes, metal or semiconductor nanoparticles are normally incorporated to serve as the active component (catalyst) for a certain catalytic reaction [44, 63, 65, 66]. When semiconductors such as TiO_2 or ZnO are employed, a light source (e.g., UV, sunlight) is needed to initiate the reaction. Thus far, the application of catalytic membranes is limited to the degradation of synthetic dyes and nitro aromatic compounds and photocatalytic antimicrobial purposes.

(iv) Antimicrobial/fouling
One of the biggest challenges of membranes in water treatment application is fouling or particularly biofouling. Fouling is the buildup of unwanted particulates onto a wetted surface. This layer of particulate tends to cause severe

loss in performance and reduces the life span of membranes. Furthermore, it results in high cleaning maintenance. Generally, there are three approaches to reduce the biofouling problems in a membrane:

1. Suppress the adhesion of biologic particulates onto the membrane;
2. Biocide leaching or toxic release;
3. Contact killing.

The first strategy involves the alteration of the surface hydrophilicity, roughness, or charges of the membranes. In contrast, the latter two strategies address the biofouling problems by incorporating inorganic species as the antimicrobial agent in the membranes. Silver nanoparticles, carbon nanotubes, oxide nanoparticles, and ammonium salts are some of the examples. Organic antimicrobial agents can also be employed. However, this is less favorable due to their poorer ability to withstand adverse processing conditions as compared to inorganic antimicrobial agents.

2.5 Cellulose-Based Composite Membranes

Cellulose is one of the most prevalent polysaccharides that is composed of repeating glucose units joined in a β-1,4-glycosidic linkage. It is abundant, naturally occurs, biodegradable, and biocompatible. Cellulose can be found in the cell walls of most plants as it gives rigidity and support to the stems. It can also be produced by some bacteria, especially from Acetobacter, Agrobacterium, and Sarcina ventriculi for various biologic purposes such as maintaining an aerobic environment and for flocculation [102]. Recently, scientists have also found that a sea animal—tunicate—can also produce cellulose to construct their body mantle. However, natural cellulose, especially plant cellulose, is insoluble in water and most organic solvents due to its closely packed structure caused by intrahydrogen bonding. This structure hampers it from further development. Hence, regenerated cellulose or cellulose derivatives are produced to overcome its processing handicap. Figure 2.4 depicts some common cellulose derivative structures that have been applied in membrane technology.

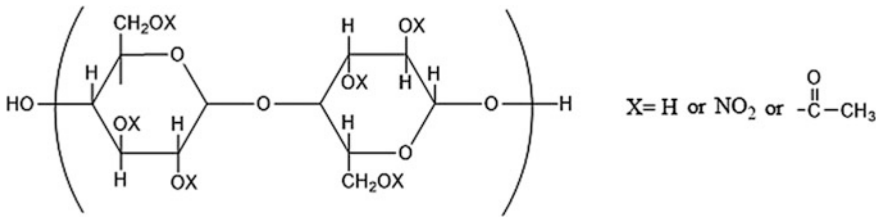

Fig. 2.4 Commonly used cellulose structures in membrane technology

The application of cellulose-based membranes in water filtration has been greatly explored since the 1960s. In fact, cellulose acetate membranes were the first membranes used in commercial reverse osmosis plants in 1965 [103]. To date, cellulose filter membranes with various pore sizes can be found commercially to remove different sizes of substances. Cellulose membranes have been used in a broad range of filtration spectra that cover from microfiltration to osmosis processes. They are capable of removing bacteria, viruses, antibiotics, pesticides, synthetic dyes, oil and grease, heavy metals, and even dissolved salts. The features of cellulose filter membranes can be improved by adding additives. Bentonite [58, 74], boehmite [75], modified coal [59], and sodium dodecyl sulfate (SDS) [47] are incorporated into cellulose to increase the water permeability of the filter membranes (higher flux) by modifying the membranes' surface porosity and hydrophilicity. Other additives such as silica [73], iron nanoparticles [51], and CNTs [61] also improve the cellulose membrane in terms of their durability and thermal and mechanical properties. Nonetheless, a decrement in salt rejection and mechanical strength has been observed when polyoctahedral silsesquioxane (POSS) nanoparticles are applied as the additives [49].

In most cases, adsorption occurs besides filtration. Positively charged heavy metal ions are favorably adsorbed onto the negatively charged cellulose membrane, while water permeates through the interconnected pores of the membrane. However, due to the low surface area of cellulose, the absorptive sites are occupied quickly by metal ions and cause a drastic drop in metal ion rejection. Complexing agents (e.g., humic acid, phytic acid), adsorbent particles (e.g., iron oxide, graphite, silica) or carriers (e.g., Calix resorcinarens) are integrated into the cellulose membranes to increase the metal removal efficiency from water. A common feature between these additives is their capability to form interaction with metal ions. For example, activated carbon and iron oxides offer negatively charged surfaces to adsorbed U(VI) and Pb(II), respectively, through complexation [46, 79]. Nevertheless, the metal removal efficiency of cellulose composite membranes is also dependent on other parameters such as pH, dopant, concentration of metal ions, and temperature [86].

The fabrication of silver–cellulose membranes and their biofouling resistance properties have been reported in many studies. Silver nanoparticles not only increase the surface hydrophilicity of the membrane, but also release the silver ions (biocides) that will eventually kill bacteria. Nevertheless, the strength of the biofouling resistance of silver–cellulose membranes is dependent on the amount, size, and the location of silver nanoparticles in the membrane. Sile-Yuksel et al. [55] conducted SEM-EDS mapping studies on a series of Ag polymer membranes and correlated them with their antimicrobial properties. They demonstrated that the silver nanoparticles located on the top layer of the membrane are easier to leach out and hence exert higher antibacterial properties. Copper oxide particles in the cellulose membranes also show superior antibacterial properties [39]. Similar to silver, its origin of toxicity comes from the leaching of metal ions.

Photocatalytic antibacterial properties of semiconductor oxides especially TiO_2 and ZnO in cellulose membranes have also been explored. Under the irradiation of light, reactive oxygen species such as OH^-, H_2O_2, and O^{2-} are generated. These oxygen species can penetrate through bacteria's cell wall and inhibit their growth [57, 63]. Besides imparting antimicrobial properties, the photocatalytic properties of these membranes can also be used for the degradation of pollutants in water. Furthermore, the presence of semiconductor oxides can lead to simultaneous improvement in membrane stability, flux permeability, and porosity [94]. Bai et al. [43, 63] have prepared multifunctional TiO_2 and TiO_2/ZnO–cellulose membranes for water purification. These membranes were used for concurrent filtration and photodegradation to remove methylene blue and humic acid with high flux and antifouling properties.

Carbon nanotubes (CNTs) and ammonium salts have been composited into cellulose to form the contact-active/contact-kill antibacterial membranes. Unlike metals or metal oxides, the application of contact-kill materials does not cause secondary contamination in the environment. The bacteria are killed once they come in contact with active sites such as CNT which are anchored to the cellulose membranes. Even though CNTs have shown promising antibacterial properties, the high cost, toxicity, and poor dispersion of CNTs in the cellulose membranes are obstacles. As such, polyvinyl-N-carbazole (PVK) has been used as a stabilizer to improve the dispersity of CNTs in cellulose and reduce the cost of membrane preparation [87]. Meng et al. [44] have modified cellulose membranes with ammonium or amino groups via alkoxysilane polycondensation reactions and assessed their antimicrobial performance. The study suggested that the bactericidal performance of the membranes is dependent on the overall molecular structure as well as the length of the alkyl group. Longer alkyl groups and higher charge density of the cationic groups enhance the interactions with the cytoplasmic membrane of the bacteria which in turn results in higher antimicrobial activity.

Cellulose composite membranes for catalytic applications are relatively less studied. Bendi and Imae [42] were the first to prepare metal-loaded cellulose membranes for catalytic reduction of p-nitrophenol in the presence of $NaBH_4$. 2,2,6,6-tetramethylpiperidine-1-oxyl radicals (TEMPO) were applied to selectively oxidize the hydroxyl group of cellulose at the C6 position to form the carboxylate groups. The carboxylate groups are responsible for the well dispersion and stabilization of Cu nanoparticles in the membrane. The resultant Cu–cellulose membranes were stable, tough, and effective even after 10 cycles. The same group of researchers [41] has also demonstrated the preparation of dendrimer-stabilized Ag–cellulose membranes and their application in the chemical degradation of rhodamine B. In this case, poly(amido amine) (PAMAM) was used as the dendrimer to protect the growth of Ag and serve as an adsorbent for rhodamine dyes. The catalytic activity of the PAMAM-stabilized Ag–cellulose membranes increases with the increase of Ag content and the surface area of the membrane by pricking it with a needle.

Semiconductor oxides such as TiO_2 or ZnO are known photocatalyst that have been used to degrade various organic pollutants. For the ease of separation, semiconductor nanoparticles are immobilized on various supports. Regenerated cellulose provides porous structures and hydroxyl groups which can effectively immobilize semiconductor oxide particles to form the composite membranes for photocatalytic purposes. The effectiveness of TiO_2/ZnO–cellulose composites as photocatalytic membranes in the degradation of phenol [43], methylene blue (MB), humic acid [40], rhodamine B (RhB) [64, 68], and methyl orange (MO) [66] was studied. Likewise, pristine TiO_2/TiO_2–cellulose catalytic membranes work well in the UV range, but less effective in the visible region. In order to widen its spectrum window, the membrane was doped with noble metals (Au and Ag) [65]. The Au- or Ag-doped TiO_2–cellulose membranes resulted in ~75 % of MB degradation as compared to undoped membranes that only gave 60 % of MB degradation.

While most of the studies on semiconductor oxide–cellulose membranes are focused on their role as solely photocatalytic membranes, Bai et al. [40, 63] have looked at the possibility of creating multifunctional membranes which can be cocurrently used for filtration, catalytic degradation, and antifouling purposes. They functionalized the surface of cellulose acetate membrane with the hierarchical $SrTiO_3$/TiO_2 [67] and TiO_2/ZnO [63] using hydrothermal method. These membranes showed excellent water purification performances with high water flux and high photocatalytic and high antimicrobial activities.

2.6 Chitosan-Based Composite Membranes

Chitosan is a polysaccharide derived from the deacetylation of chitin. It is abundantly applied in a wide range of applications, as a stabilizer and an adsorbent, mainly due to its unique structure that consists of functional groups such as amino and hydroxyl groups [104]. This environmentally friendly material can be shaped into various forms. As an example, beads, powder, sponge, membranes , and hallow fibers are among the numerous structures of chitosan which have been developed. The intention of chitosan in the form of hallow fibers, beads, and sponge is mainly to enable the increase in its surface area and porosity. Increase in surface area and porosity is commonly related to enhanced adsorption, filtration, etc. However, this is not always advantageous, especially for chitosan-based membranes mainly because of its brittleness and due to the fact that it can agglomerate easily in an aqueous medium [30, 105].

As an adsorbent or filter, chitosan-based membranes have been used for the removal of transition metals as well as organic molecules. For added value, researchers have been challenged to find additives which are economical while maintaining its environmentally friendly characteristics. Metal ions such as Cu ions have been removed using thin composite membranes of chitosan/polyvinyl alcohol with MWCNT-NH_2 [30]. Apart from metal ions, the adsorption of humic acid using polyacrylonitrile-coated chitosan impregnated with amine-stabilized magnetite nanoparticles has also been reported [36]. Other works reported are on montmorillonite (MMT)/chitosan for the adsorption of Bezaktiv Orange V-3R dye [27], mesoporous carbon/chitosan for the adsorption of fuchsin [24], chitosan/PEG/CNT for the adsorption of methyl orange [106], and thin composite membranes of TiO_2/

chitosan/glass plate for the adsorption of Reactive Red 4 [23]. In the later work, the thin composite membrane offers several advantages. Apart from a bifunctional photocatalysis—adsorption system, the TiO_2 shields the chitosan from direct exposure to the irradiation source which can ultimately change the structure of chitosan and its adsorption capacity.

Other bifunctional systems that have been put forward are for filtration and antifouling purposes. Zinadini and coworkers described the use of PES membranes incorporated with O-carboxymethyl chitosan-bound magnetite nanoparticles for filtration of Direct Red 16 dye. Here, the magnetite was employed as a support for chitosan [37]. The membranes exhibited superior pure water flux, higher rejection of dyes, and good antifouling properties as compared to unmodified PES membranes. Fouling generally deteriorates a membrane and causes hikes in operational costs. Current membranes are composed of a reinforcing fabric polymer, followed by a layer of polysulfonic and polyamide. Modification of the upper polyamide layer with graphene oxide and chitosan improves the fouling resistance characteristics of the membrane by two modes: first by increasing the hydrophilic nature of the membrane and reducing its surface roughness and second by enhancing the electrostatic repulsion between membrane surface and protein molecules [38].

Various studies on the use of chitosan as a membrane for catalytic application have also been reported. In these studies, it is interesting to note that most researches have favored to shape the membranes in the form of hallow fibers or nanofibrous [25, 28, 29]. This gives the advantage of increasing the surface area in which the catalytic membrane can be exposed to the substrate. The chitosan in these catalytic membranes mainly functions as a support or stabilizer for the active phase for a particular catalytic reaction. As an example, Seyed Dorraji and coworkers [25] prepared chitosan-supported Fe_3O_4 membranes. They compared the use of pure cross-linked chitosan and chitosan/Fe_3O_4 for the degradation of the dye, Reactive Blue 19. They reported that chitosan/Fe_3O_4 was only slightly effective as a catalytic membrane when compared to its corresponding pure chitosan hallow fiber. In the presence of chitosan/Fe_3O_4, adsorption of the dye occurred. In contrast, in the presence of hydrogen peroxide, H_2O_2, the Fenton-like reaction occurs, resulting in the generation of OH radicals. This improves the performance of the catalytic membranes drastically whereby degradation of the dye occurs simultaneously with its adsorption. Another work in which chitosan/Co phthalocyanine membranes were prepared for the degradation of rhodamine B has also been reported [26]. The authors did not typically form catalytic membranes via electrospinning technique. However, to optimize the available surface area, double-layer membranes were prepared. The membranes showed excellent degradation efficiency of up to 99 % within 60 min. Even so, the authors noted that this was achievable at pH values of 6 and below. Higher pH values resulted in a significant decrease in the extent of rhodamine B degradation. From a realistic perspective, this may pose a problem in terms of the reusability of the membranes, as chitosan dissolves at pH values of <4.

Enzymes, specifically laccase, have also been immobilized on nanofibrous membranes composed of chitosan and poly(vinylalcohol) [29] as well as chitosan/poly(vinylalcohol)/multiwalled carbon nanotubes (MWCNT). In these works, chitosan/poly(vinylalcohol) gels were prepared to improve the mechanical strength of chitosan. This improves spinnability during electrospinning to form the nanofibrous membranes [29]. Laccase which is a multicopper oxidase is immobilized to the chitosan covalently via the formyl groups of glutaraldehyde that have shown to be effective for the degradation of 2, 4-dichlorophenol [29]. To improve the catalytic effect of laccase, an electron transfer agent like multiwalled carbon nanotubes can be introduced into the chitosan/poly(vinylalcohol) [28]. This novel approach has proven to eliminate diclofenac successfully as compared to nanofibrous based on chitosan/poly(vinylalcohol) [28].

2.7 Natural Rubber-Based Composite Membranes

Natural rubber (NR) is obtained from the tree Hevea brasiliensis. Its latex consists of three phases, namely the rubber, aqueous, and lutoid phase [107]. The rubber phase comprises of spherical to oval particles which consist of repeating cis-1,4-polyisoprene units. These particles are surrounded by a layer of proteins such α-globulin. The aqueous phase on the other hand contains carbohydrates, proteins, and amino acids, while the main component of the lutoid phase is water, protein, and phospholipids [107]. In general, the protein in natural rubber plays an important role. It prevents coagulation of the rubber particles and provides binding sites for additives such as metal nanoparticles [108]. This is mainly attributed to the availability of –COOH and –NH_2 functional groups in the proteins.

To date, the use of natural rubber-based composite membranes in wastewater treatment is limited. Several works have appeared for adsorption and catalytic purposes. However, none have reported on its use for filtration and antibacterial/fouling. The main reasons for the lack of research in these areas may be due to the nature of natural rubber which lacks porosity and hydrophobicity. For adsorption, epoxidized natural rubber (ENR)-incorporated magnetite-mixed matrix membranes has been used for oil recovery [88]. Adsorption of the oil was promoted by the hydrophobicity and porosity of the membrane itself. The porous structure of ENR was formed via dissolution of SiO_2 (incorporated during synthesis) with HF. The addition of magnetite into the natural composite membranes allows magnetic recovery.

In another work, thin-film composites composed of layers of NR, SiO_2, and TiO_2 have been used for the photocatalytic degradation of methylene blue [109]. The authors reported that TiO_2 not only aided in the degradation of the dye but also improved the life span of the NR. Sriwong et al. [110] also conducted a detailed study comparing the performances of powder TiO_2 with TiO_2-supported NR membranes for the degradation of methylene blue. In this work, both systems demonstrated comparable efficiencies; however, powder TiO_2 exhibited a faster degradation time. Although these works are interesting, both were carried out before the year 2010. Since then, only Nawi et al. [89] have reported a study on thin-film composite membranes comprising of TiO_2, ENR, and PVC for the degradation of dyes. Our group has also actively investigated NR-based composite membranes for the degradation of methylene blue in the presence of borohydride [111] and methyl orange using a UV light [112]. In these works, NR-Ag films were prepared via soft thermal treatments. Results show that the NR-Ag membranes were effective for the degradation of both dyes.

2.8 Future of Natural Composite Membranes

To what extent is it 'green'? This is one of the questions which frequently pop up when the topic of discussion circulates around renewable materials. When discussing natural composite membranes, the extent to which it is 'green' can be reflected from several aspects, that is, the preparation, materials, and function of the membrane.

Basically, the technique with which natural composite membranes are prepared should be environmentally friendly. This means that the overall process should not create secondary pollutants and consumes less energy. For this matter, considerations such as the method to cross-link or graft polymers should be scrutinized. The use of microwaves or UV irradiation as an alternative to solvents may be a more viable option in this sense. In terms of materials for natural composite membranes, 'green' can be accomplished by minimizing the use of any toxic materials during or in its fabrication. Avenues which have yet to be explored in depth are the use of ionic liquids as solvents or solely renewable materials such as natural polymers reinforced with agricultural waste for the fabrication of membranes. It is undeniable that work has been done on such composites for instance natural rubber reinforced with peanut shell powder [113]. Unfortunately, there has been a lack in the use of these composites for wastewater treatment. Another aspect that should be looked at is the persistency of these natural composite membranes in the environment. Additives in the natural polymer membranes can change the degradability of the composite membranes. As such, an active role should be taken to ensure that the membranes can easily be degraded after its life span. From a functionality point of view, the current situation with natural composite membranes is that most of these membranes are constricted to monofunctions. The development of multifunctional or hybrid natural membranes is still at its infant stage and should be given more focus in future as compact industrial designs save space and energy, which is more economical. Furthermore, these multifunctional membranes allow the possibility of creating membranes with superior removal efficiency and selectivity.

Although these ideas can pave a way toward a sustainable tomorrow, in reality detailed technical study is required to bridge the gap between laboratory-scale and industrial applications. In the past years, there has been significant achievement in the fabrication of numerous natural composite membranes. Generally, most of these membranes have showed promising performances. However, it has to be pointed out that the achievements accomplished are only at laboratory scale.

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Chapter 3
Polymeric Heat Exchangers: Effect of Chemistry and Chemical Composition to Their Performance

Mohd Firdaus Yhaya

Abstract Polymers can be used to construct heat exchangers, provided the polymer selection and design are done correctly. Despite their limitations, many types of thermoplastic polymers (thermoplastics) are being used as heat exchangers as compared to thermosetting polymers (thermosets). Properties of polymers are by large influenced by their chemical compositions and molecular weight. Based on current trends, the future outlook for polymers as heat exchangers is bright.

Keywords Heat exchanger · Thermoplastic polymers · Thermosetting polymers · Chemical compositions

3.1 Introduction

In the past, metals have been the materials of choice to construct heat exchangers. Polymers have been used only as the coating layer to prevent corrosion. As the technology and time progress, polymers were selected to build the heat exchangers. Polymers are large molecules made up from the repetition of subunits (monomers). In general, polymers have lower thermal stability and conductivity [1], problems with creeping, degradation, and lack of mechanical properties relative to metals. However, they have already been used as heat exchangers for many years due to benefits such as corrosion resistant, lightweight, low cost as compared to exotic metals, easy to manufacture, ability to handle both liquids and gases, and inherent resistance to fouling [2–4]. Lower thermal conductivity of polymers may be overcome with the thin sheet design. Unlike metals, the properties of polymers are highly dictated by their molecular weight and chemical compositions. Higher

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molecular weight may give better physical properties and chemical resistance. In comparison with the reviews readily available in the literature, this chapter will put more emphasis on the chemistry of the polymers and its effect on the performance of heat exchangers. However, this chapter does not meant to be exhaustive, and some examples may have been left out.

The use and design of any polymer as heat exchanger must take into account the working environment that will be faced by the exchanger during its service life in domestic or industrial applications. For example, tropical countries are generally hotter with higher humidity as compared to temperate countries which have cooler and drier air. Acids may weaken heat exchangers made from polyamide-imides, polyarylates, polyimides, polysulfones, and polyetheretherketones. Polymers that contain aromatic rings, such as polystyrene (PS), epoxy resins, polyether sulfones, and polyetheretherketones, are susceptible to ultraviolet (UV) ray and must be protected against sun. In addition, thermoplastics such as polyethylene, polypropylene, and PS are not suitable to be used against streams of organic solvents that are known to dissolve them. The general rule "like dissolves like" is applied here. Polymers tend to dissolve in solvents with similar chemical structures; for example, PS dissolves in benzene, toluene, and xylene. Polymers with polar groups will attract polar solvents (like water) and vice versa. The determination of suitable solvent/solvent mixture could be determined by calculating the solubility parameter. In terms of design, the heat exchangers may be designed as corrugated sheets or smaller diameter tubes to increase the surface area. Polymeric heat exchangers may also be designed as thin layers to overcome the problem of lower thermal conductivity.

There are two approaches taken when developing heat exchangers related to water in either liquid or gas phase. First, the polymers used are totally hydrophobic (water-hating) so that the water can be pushed away and does not wet the surface. Second approach is that the polymers are hydrophilic (water-loving) so that the water molecules are attracted to the surface by hydrogen bonding, forming a thin layer.

Another factor to be considered is the transition temperatures which are glass transition temperature (T_g) and melting temperature (T_m). A polymer, upon heating, will transform from a rigid material into soft and rubbery material. The temperature at this moment is called the T_g of the polymer. Continuous heating will change the soft and rubbery physical state into a molten state (liquid). At this moment, the temperature is said to be the T_m of the polymer. 100 % amorphous polymer will only show T_g, while 100 % crystalline polymer will only show T_m. However, most polymers are semi-crystalline, which explain the existence of both transition temperatures. Polymers with fillers may show different thermal transitions, while thermosets are usually amorphous with cross-linked three-dimensional structures. Differential scanning calorimetry (DSC) can be used to determine these transition temperatures of a polymer of interest.

Environmental stress cracking (ESC) factor may also affect polymeric materials, especially amorphous thermoplastics. ESC is different from degradation because it is not that the polymer backbones are broken but the secondary linkages between polymer chains. Mechanical stress or chemical alone may not be enough to cause failure, but combination of both will initiate small cracks (crazes) at the surfaces. After crazes are formed, the chemical (solvent) may diffuse and weaken the polymer even more. Once inside, the solvent molecules may act as plasticizer to reduce the glass transition temperature of that polymer. ESC may weaken the polymers over long period of time, so the maximum service temperature may be reduced. Increasing the molecular weight of the polymer may solve this problem.

Typically, polymers are expected to have lower thermal conductivity as compared to metals. Temperature, pressure, density of polymer, orientation of chain segments, crystal structures, degree of crystallinity, and other factors may significantly affect the thermal conductivity of polymers [5]. The presence/addition of conductive filler such as graphite may increase the thermal conductivity of polymers of interest [6]. Foaming of polymers may reduce the thermal conductivity due to the voids, while increasing the temperature will increase the thermal conductivity. Aromaticity and heterocyclicity usually contribute to rigidity and heat resistance of polymers. If the heat exchanger is made of polymer composite/s, compatibility must be ensured between fillers/reinforcement and polymeric matrices so that delamination will not occur. In terms of sustainability, these polymers found their origin from non-renewable resource such as petroleum. Despite this fact, they can be turned up into products for sustainability such as heat exchangers.

3.2 Types of Polymers Used as Heat Exchangers

Polymers, in some context, are known as plastics, and both terms are used interchangeably. They can be described as large molecules (macromolecules) made of repetitive units called monomers. In general, polymers can be divided into two major groups: thermoplastics and thermosets. Thermoplastics usually contain linear molecular chains of different length. They can be melted by heat or dissolved in solvents. The removal of heat or solvents will return them back to solid state. This cycle can be repeated many times. On the other hand, thermosets begin with lower molecular weight precursors which are usually in liquid state. These precursors are later joined together to form a solid consisting of molecules linked in three-dimensional network. This network is permanent; neither heat nor solvent can return them back to their original liquid state. In other words, thermoplastics obtain their physical strength by having linear, high molecular weight chains right from the start, while thermosets do so by cross-linking (networking) of the low molecular weight precursors.

3.2.1 Thermoplastics

3.2.1.1 Vinyl Polymers: Polyethylene (PE), Polypropylene (PP), Polybutylene (PB), Polyvinyl Chloride (PVC), Polystyrene (PS), Polymethyl Methacrylate (PMMA), Polyvinyl Alcohol (PVOH)

Vinyl polymers are made thermoplastic polymers from monomers that have basic structures of –$CH=CH_2$ (Fig. 3.1) by free radical polymerization. Polymers made by this technique tend to have chains with long carbon to carbon backbones. However, the length of each chain may be different. If the polydispersity index (PDI) of any polymer is close to 1 (to become narrower), that means the entire polymer chains are of the same length. Protein is one example of natural polymer that has PDI of 1. For synthetic polymers, lower PDI can be achieved by using controlled free radical polymerization techniques, such as atom transfer radical polymerization (ATRP), nitroxide-mediated polymerization (NMP), and the ever popular reversible addition–fragmentation chain transfer polymerization (RAFT) [7].

PE, PP, and PB are polyolefins, a group of polymers made of alkenes. These polymers consist solely of hydrogen and carbon atoms, which make them hydrophobic. They are generally inert, non-toxic, and very low in density. PE is low in density due to the small amount of branching along its backbone. Robust yet flexible, it is chemically unreactive at room temperature. However, it may be

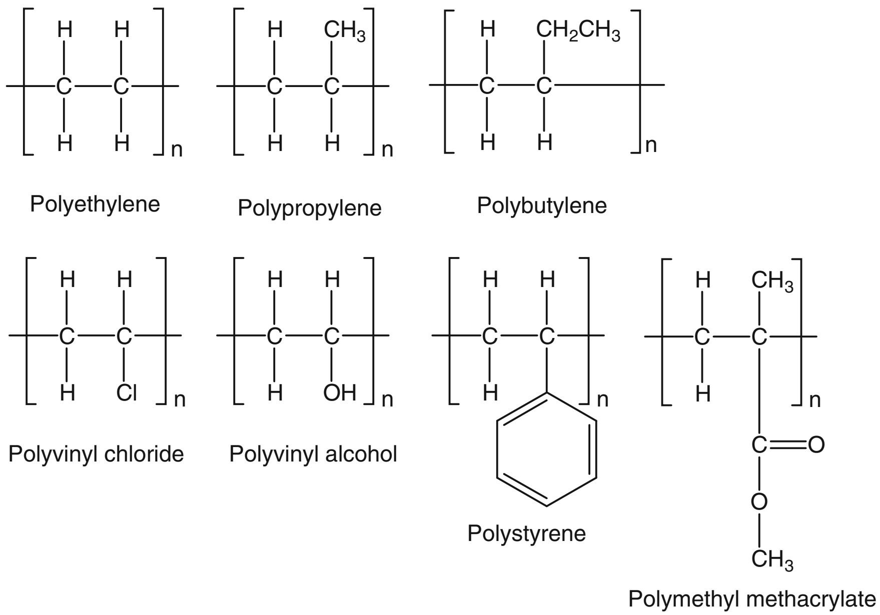

Fig. 3.1 Chemical structure of vinyl polymers used as heat exchangers

weakened by strong oxidizing agents and some organic solvents. In order to increase the thermal conductivity, PE has been filled with acetylene black. PE has lower operating temperature range than PP. PP is more rigid but attacked by oxidizing agent much faster than PE. PP has the highest melting point among other hydrocarbon polymers. PB is resistant to chemicals, hydrostatic pressure, and impact forces. However, PB may experience ESC with chlorinated water aggravated by tensile stress. All these three polyolefins are currently used as heat exchangers for both building and environmental applications.

PVC is a rigid polymer with resistance to oxidation, acids, alkalis, and almost all inorganic chemicals. This explains the popularity of PVC as a plumbing material. PVC has superior fire retardancy due to its chlorine atoms and the lowest heat release upon burning among other polyolefins. Once burned, PVC will release toxic hydrogen chloride (HCl) gas to the environment. The polar chlorine atoms impart hydrophilicity to the polymer. PVC can be plasticized to reduce its rigidity so it can be turned into imitation leather products. PVC is used in building and environmental applications.

PS is available as foam or hard, brittle solid. PS is resistant to acids and bases but attacked by chlorinated and aromatic hydrocarbon solvents. PS is normally grafted with polybutadiene to reduce the brittleness. Since it is also made of hydrocarbon (nonpolar), it is hydrophobic. Due to its aromatic rings, PS suffers from low UV stability. PS is mostly used to construct heat exchangers for building applications and may be filled up with graphite to increase the thermal conductivity [8].

PMMA is a thermoplastic normally used as a substitute for glass due to its clarity and lightweight. PMMA is a cheaper substitute for polycarbonate when strength is not critical. Easy to handle with low cost, PMMA is a brittle polymer with low scratch resistance. It has poor resistance to organic solvents and chemicals as a result of ester group (–CC=OOCH$_{3-}$) which is easily hydrolyzed. Nevertheless, PMMA is resistant to environments which explain its widespread use as cover for automotive taillights. PMMA can be used for building and environmental applications, provided its limitations are taken into consideration.

PVOH is soluble in water and is the most hydrophilic polymer ever, due to the abundance of hydroxyl groups (–OH) along the backbone. Compared to others, it is not made of vinyl alcohol monomer due to it instability with respect to acetaldehyde. Vinyl acetate (VA) is polymerized first in order to obtain polyvinyl acetate (PVA), which later is converted into PVOH by transformation of acetate groups into hydroxyl groups. Cross-linking is done to prevent PVOH from dissolving in water at the expense of hydroxyl groups.

3.2.1.2 Fluoropolymers: Polytetrafluoroethylene (PTFE), Polyvinylidine Fluoride (PVDF), Perfluoroalkoxyl (PFA)

Fluoropolymers have good resistance to acids, bases, and solvents due to the strong carbon to fluorine bonds (Fig. 3.2) [9]. They have nonstick properties with low coefficient of friction. In general, fluoropolymers have service temperature higher

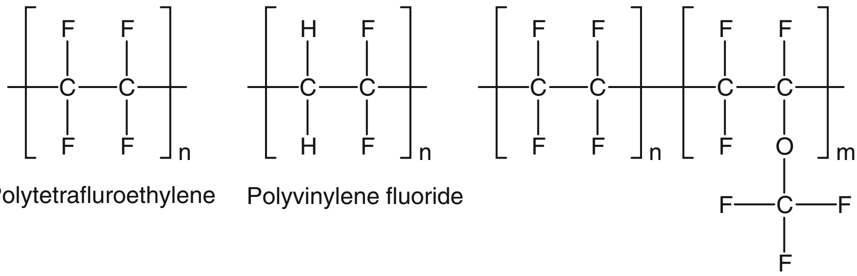

Fig. 3.2 Chemical structure of fluoropolymers used as heat exchangers

than 200 °C. The most valuable property of fluoropolymers is the flame retardancy conferred by the fluorine atoms along the backbone. The flame resistance, chemical resistance, and higher continuous service temperature increased as the amount of fluorine is increased. Most fluoropolymers found use in industrial applications rather than domestic (building) due to these qualities.

PTFE (Teflon®) is universally known for its nonstick property as nonstick pans and tapes. It has the lowest coefficient of friction of any polymers but high wear rating [10]. However, PTFE is susceptible to molten alkali metals and fluorinating agents. Alkali metals will remove the fluorine atoms from PTFE. PTFE will "creep" over time since it cannot be cross-linked due to chemical inertness. Later, electron beam is used to produce cross-linked PTFE with high-temperature mechanical properties and radiation stability. DuPont® had managed to increase the surface area of PTFE heat exchangers by bundling small tubes together [4].

PVDF can withstand high temperatures, chemicals, and mechanical stresses. It has good membrane-making properties and mainly used as separators in industrial applications [11]. Other important application is as insulation material for electrical wiring. PVDF is soluble in some organic solvents, including N,N-dimethyl acetamide (DMAc), dimethyl formamide (DMF), and N-methyl-2-pyrrolidone (NMP). PVDF is easier to process relative to other fluoropolymers.

PFA is similar to PTFE as far as the properties are concerned. The alkoxy (–O–CF_3) substituents allow PFA to be easily processed than PTFE.

3.2.1.3 Polyethylene Terephthalate (PET)

PET (Fig. 3.3) is polyester made by polycondensation of ethylene glycol with terephthalic acid or dimethyl terephthalate. It is mainly produced into synthetic fibers and water bottles. PET is hygroscopic, which means that it will absorb water form the surrounding. However, PET has poor UV resistance and cannot be used at temperature above 150 °C because of thermal oxidation. PET may be subjected to

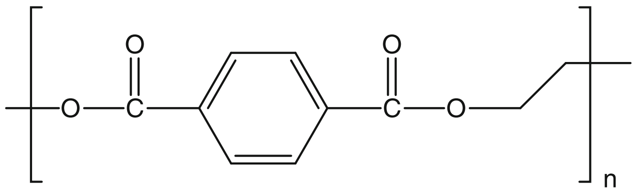

Fig. 3.3 Chemical structure of polyethylene terephthalate

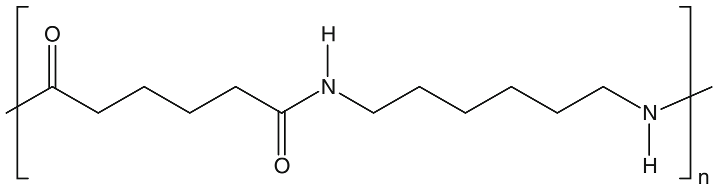

Fig. 3.4 Chemical structure of Nylon 6,6

hydrolysis with the presence of bases, especially at higher temperatures. PET is mainly used for building applications [12].

3.2.1.4 Nylon 6,6 (Nylon 66)

A polyamide out of polycondensation between hexamethylenediamine and adipic acid, Nylon 6,6 (Nylon 66) has repeating amide group (–NHCO–) along the backbone (Fig. 3.4). It has high mechanical strength plus resistant to heat and chemicals. Nylon 66 obtains its mechanical strength from the intermolecular hydrogen bonding, while other thermoplastics depend on the aromatic rings in the backbone. Due to the capability of making hydrogen bonding, Nylon 66 tends to absorb moisture. This will cause premature failure if Nylon 66 is exposed to hot aqueous environment for an extended period [13]. It loses out to Kevlar® due to the aromatic rings in place of linear hydrocarbon backbone in Nylon 66. Oxidizing agents, strong acids, and bases may attack Nylon 66. It is used for solar water heating system in buildings.

3.2.1.5 Polyether Sulfone (PES)

PES (Fig. 3.5) is synthesized by polycondensation reaction between bisphenol A (BPA) and bis(4-chlorophenyl) sulfone. It has the advantages of being flame retardant and dimensionally stable at high temperatures. Due to the heat stability, PES needs to be processed at high temperature. PES is highly resistant to acids, alkalis, oxidizing agent, and oils but susceptible to ketones, chlorinated, and

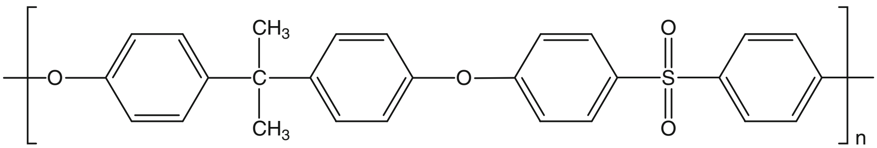

Fig. 3.5 Chemical structure of polyether sulfone

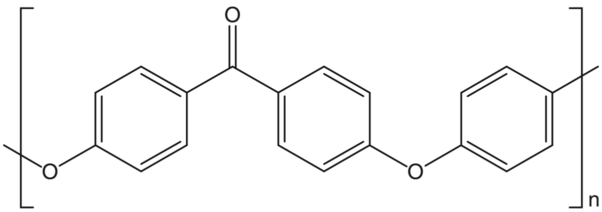

Fig. 3.6 Chemical structure of polyether ether ketone

aromatic hydrocarbons. PES is inherently hydrophilic due to the sulfone (R–SO_2–R) groups and is able to withstand high temperature in air or water for prolonged periods. PES is normally used in specialty applications such as filtration membranes due to the high cost of raw materials and processing.

3.2.1.6 Polyether Ether Ketone (PEEK)

PEEK (Fig. 3.6) is obtained from the reaction between 4,4'-difluorobenzophenone and the disodium salt of hydroquinone. It has excellent mechanical properties and high chemical resistance even at high temperatures. PEEK also can withstand organic solvents and high-pressure, high-temperature aqueous environment. Due to these qualities, PEEK heat exchangers are utilized in industrial and environmental applications. Concentrated nitric and sulfuric acid were found to attack PEEK [2].

3.2.1.7 Polyphenylene Oxide (PPO)

Synthesized from 2,6 dimethyl phenol, PPO (Fig. 3.7) is a brittle polymer with a very high heat resistance up to 195 °C. The rigidity is provided by the alternating aromatic rings. This is the reason why PPO as a homopolymer alone is difficult to process. Usually, it is blended with high-impact polystyrene (HIPS) to impart flexibility and to reduce the glass transition temperature. It also has flame retardancy and low water absorbency but poor chemical resistance and UV stability. PPO is more suitable to industrial and environmental applications.

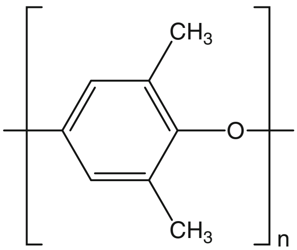

Fig. 3.7 Chemical structure of polyphenylene oxide

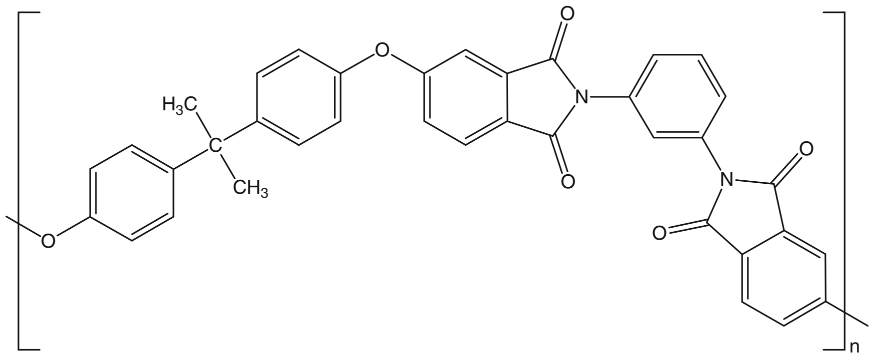

Fig. 3.8 Chemical structure of polyether imide

3.2.1.8 Polyether Imide (PEI)

PEI (Fig. 3.8) is made of polycondensation between m-phenylenediamine and bisphenol A dianhydride. PEI has high tensile strength, superior dimensional stability at elevated temperatures, flame retardancy, and resistant to organic solvents. PEI heat exchangers are suitable for industrial and environmental applications. PEI has certain drawbacks, namely expensive, difficult to color, and prone to ESC in chlorinated solvents.

3.2.1.9 Polyphenylene Sulfide (PPS)

PPS (Fig. 3.9) is formed by reaction of p-dichlorobenzene and sodium sulfide. It is very strong and has exceptional resistance to acids, alkalis, heat, bleaches, UV light, solvents, and abrasion. In addition, it is also has inherent flame retardancy. PPS tends to brittle and warp, which can be overcome with the inclusions of fillers and fibers. In acidic conditions, PPS was found to be the best performer as compared to PTFE and PVDF [3]. The thermal conductivity of PPS was improved up to

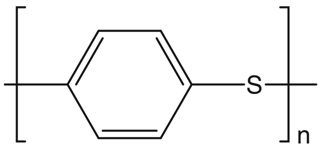

Fig. 3.9 Chemical structure of polyphenylene sulfide

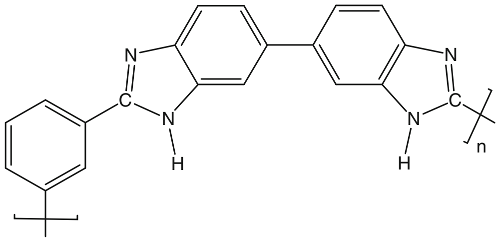

Fig. 3.10 Chemical structure of polybenzimidazole

10 W/m-K by adding carbon fibers [4]. PPS heat exchangers found use in building and environmental applications.

3.2.1.10 Polybenzimidazoles (PBI)

A polycondensation product between diphenyl isophthalate and 3,3',4,4'-tetraaminodiphenyl, PBI (Fig. 3.10), has high thermal, chemical, and flame resistance. Firefighters' protective gear, membranes, and fuel-cell electrolyte are the end products of PBI. PBI has better moisture absorption than other synthetic fibers due to the imidazole groups which can attract water molecules. PBI heat exchangers are suitable for industrial and environmental applications.

3.2.1.11 Polybenzothiazole

A heterocyclic aromatic polymer with outstanding thermal stability [14], polybenzothiazole (Fig. 3.11), is made by a reaction between 3,3'-mercaptobenzidine and diphenyl phthalate. Due to the rigidity of the rings, polybenzothiazole exhibits high modulus, high strength, and resistant to the environment. Therefore, polybenzothiazole is suited for industrial and environmental applications.

3.2.1.12 Liquid crystal polymers (LCPs)

LCPs are aromatic polymers with highly ordered structures in either molten or solid states. They are mechanically strong with superior resistance to heat, chemical, and radiation (except UV). LCPs resist ESC of most chemicals at elevated temperatures. The most popular LCP is Kevlar® followed by Vectran® (Fig. 3.12). Kevlar® is

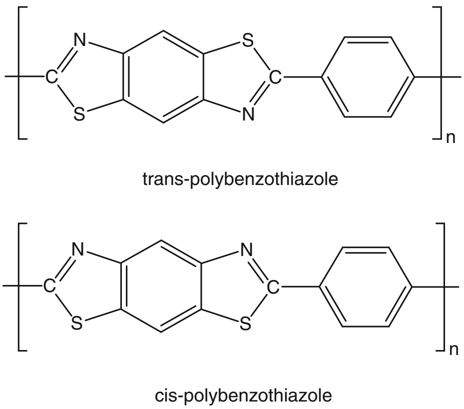

Fig. 3.11 Trans and cis form of polybenzothiazole

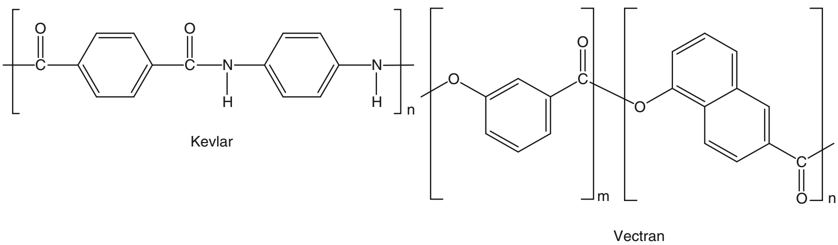

Fig. 3.12 Chemical structure of popular liquid crystal polymers

made by polycondensation of terephthaloyl chloride and 4-phenyl-diamine (*para*-phenylenediamine). Vectran® is produced by the polycondensation of 3-hydroxybenzoic acid and 5-hydroxynaphthalene-2-carboxylic acid. As expected, the main downside of LCP is their high cost and their poor resistance to UV light. LCP heat exchangers are used in industrial and environmental applications.

3.2.1.13 Polycarbonate (PC)

PC (Fig. 3.13) is produced by polycondensation reaction between BPA and phosgene. It has high-impact resistance but poor scratch resistance. PC can withstand large deformation without cracking, making it suitable to be processed into any shapes. This is the most valuable property to engineers and architects as it gives them the freedom in designing. It is resistant to acids (organic and mineral) and oils but not to alkalis, nitriles, ammonia, amines, polyamides, and organic solvents. PC has the tendency of yellowing and becoming weak upon exposure to UV radiation

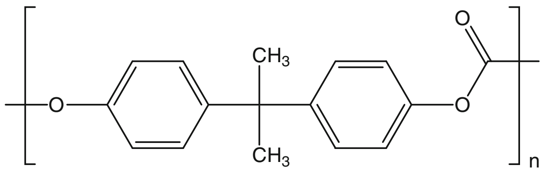

Fig. 3.13 Chemical structure of polycarbonate

due to the absorbance of UV light by the aromatic rings. PC heat exchangers are popular for building applications.

3.2.2 *Thermosets*

3.2.2.1 Epoxies

The most popular epoxy resin (Fig. 3.14) is BPA based, even though other varieties are also available. BPA is reacted with epichlorohydrin to form diglycidyl ethers of BPA. The most reactive part is the epoxy group (oxirane), and a reaction with polyamines will form a cross-linked (cured) epoxy resin. The epoxide content reduces with the increase in the molecular weight of the resin. The epoxy resin becomes more thermoplastic with more hydroxyl groups along the backbone (more hydrophilic). After curing, epoxy resin exhibits strong adhesion, low shrinkage, resistant to heat, and chemicals but not UV light. Epoxy heat exchangers are used in industrial applications.

3.2.2.2 Phenolics

Phenolics (phenol-formaldehyde, PF) (Fig. 3.15) refer to the cross-linked products between phenol and formaldehyde. Curing is achieved by heating. Phenolics have good dimensional stability coupled with heat and electrical insulation. However, these types of resins tend to release formaldehyde over time during their service. Similar to epoxies, phenolics heat exchangers are popular in industrial applications.

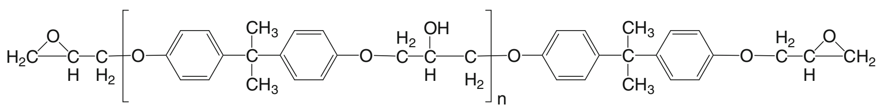

Fig. 3.14 Chemical structure of BPA-based epoxy resin

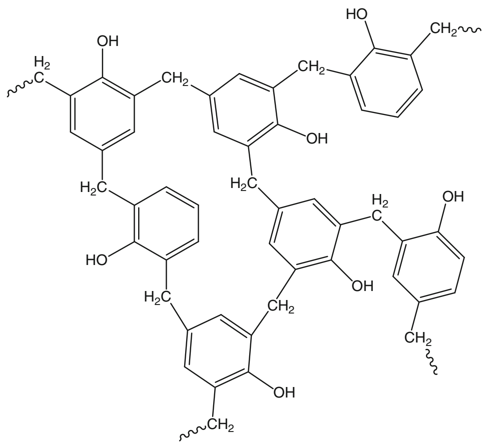

Fig. 3.15 Chemical structure of phenolics

3.2.2.3 Unsaturated Polyesters (UPs)

UPs (Fig. 3.16) are made by polycondensation reaction of polyols with unsaturated dibasic acids. The common polyols are ethylene glycol, propylene glycol, or glycerol, while unsaturated dibasic acid is maleic acid/anhydride. Saturated dibasic acid such as phthalic acid/anhydride may be added to increase rigidity. After polycondensation, the resin may be cross-linked with styrene with peroxide

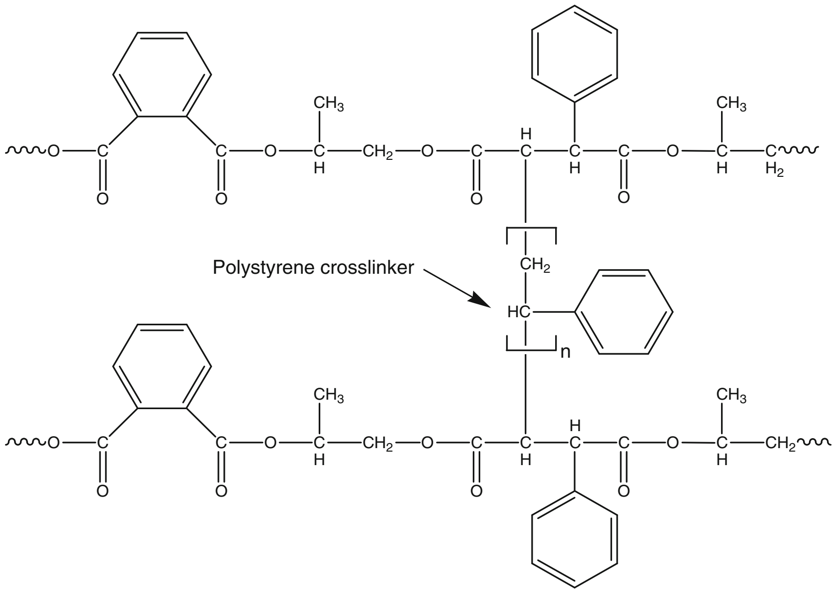

Fig. 3.16 Chemical structure of unsaturated polyesters

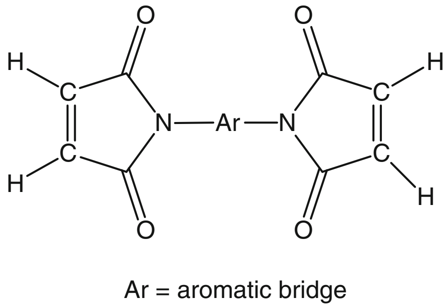

Fig. 3.17 Chemical structure of bismalaimides

initiator. UP resins are low cost, easy to process, and easily pigmented. They have good resistance to dilute acids, alkalis, and alcohols but poor resistance to hydrocarbons. UP heat exchangers may find applications in the industry.

3.2.2.4 Bismalaimides (BMI)

BMI resins (Fig. 3.17) are relatively new class of thermosetting polymers which find use in aerospace applications. They have good property retention at high temperatures and wet environments up to 250 °C. High temperature stability of BMI is good for industrial applications. Easily processed, they possess flame and radiation resistance with good mechanical, thermal, and electrical properties. BMI resins cured (cross-linked) thermally by opening of the –C=C– double bonds [15]. The cured resins, however, are brittle due to the high cross-link density.

3.2.3 Properties of Polymeric Heat Exchangers

Typically, polymers are expected to have lower thermal conductivity as compared to metals. Temperature, pressure, density of polymer, orientation of chain segments, crystal structures, degree of crystallinity, and other factors may significantly affect the thermal conductivity of polymers [5]. The presence/addition of conductive filler may increase the thermal conductivity of polymers of interest [6]. Foaming of polymers may reduce the thermal conductivity due to the voids, while increasing the temperature will increase the thermal conductivity. Aromaticity and heterocyclicity usually contribute to rigidity and heat resistance of polymers. Polymeric heat exchangers may be designed as thin layers to overcome the problem of lower thermal conductivity. If the heat exchanger is made of polymer composite/s, compatibility must be ensured between fillers/reinforcement and polymeric matrices so that delamination will not occur. Another factor to be considered is that the ESC may weaken the polymers over long period of time, so the maximum service temperature may be reduced.

3.3 Conclusion

The thermal properties of polymeric heat exchangers are summarized in Table 3.1. Properties of polymers are largely influenced by their chemical structures and compositions. The aromatic rings provided the polymers with rigidity but at the

Table 3.1 Thermal properties of polymeric heat exchangers with comparison to metals

	Thermal conductivity at 23 °C (W/m.K)	Maximum service temperature/range (°C)
Thermoplastic		
PE [2]	0.35–0.52	110
PP [2]	0.20	80
PB	0.22 [16, 17]	[13]
PVC [2]	0.15	60
PS [2]	0.10–0.15	Not available
PMMA [2]	0.20	Not available
PVOH	Not available	Not available
PTFE [2]	0.25	−73–260 [18]
PVDF [2]	0.18	140
PFA	0.25	300 (approximate)
PET	0.15 [5]	Not available
Nylon 6,6	0.20–0.25	about 200
PES	0.13–0.18	190 [2]
PEEK	0.25 [19]	250 [2]
PPO	0.22	150 (approximate) [2]
PEI	0.22	150 [2]
PPS	20 [20]	170 [2]
PBI	0.41	300 [2]
Polybenzothiazole	Not available	400–480 [2]
LCP	0.04 (Kevlar), 0.33–0.52 (Vectra)	>300 [2]
PC	0.19–0.22	−4–135 [19]
Thermosets		
Epoxies	0.10–1.70 (unfilled), 1260 (filled) [21]	135 [18]
Phenolics	0.15 [6]	Not available
UP	Not available	Not available
BMI	Not available	300 (approximate) [2]
Metals		
Mild steel [2]	60	Not available
Copper [2]	397	Not available
Aluminum [2]	240	Not available
Titanium [2]	22	Not available

expense of UV light stability. The future of polymeric heat exchangers is predicted to be built upon these four bases: new polymers, new reinforcement or additives, new design, and new fabrication techniques. In the future, polymer heat exchangers are expected to perform under more stringent regulations related to energy recovery and environment protection.

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Chapter 4
Solar Induced Ventilation Strategy in Contemporary Tropical Buildings: A Review

Mazran Ismail and Abdul Malek Abdul Rahman

Abstract Recent development in passive cooling studies have shown that stack ventilation could be a potential strategy in providing effective natural ventilation strategy for a building in the windless region, and in the deep plan building where cross ventilation has limited function. However for the building in tropical climate where the indoor–outdoor temperature differential is very low, this strategy is often regarded insignificant to provide sufficient ventilation needed for occupants comfort. This constraint has prompted several researchers to develop some solar induced ventilation strategies that can maximize free energy available from the sun and high solar radiation of tropical climate to heat building cavities and increase the temperature difference, thus improving the applicability of the stack ventilation strategy in suctioning the indoor air and extracting it out through the upper outlet areas. This book chapter presents the potential and limitations of the solar induced ventilation strategy in the tropical region, particularly in its subtypes of tropical rainforest climate and tropical monsoon climate by discussing its ventilation performance based on the results of previous studies, state-of-the art technologies and several significant examples of its applications in the contemporary tropical buildings.

Keywords Stack ventilation · Solar induced ventilation · Thermal environment · Tropical building

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4.1 Introduction

Numerous studies have shown that buildings consume about 30–40 % of the world's energy demand and it is expected to increase rapidly to 50 % by the year 2030 [1, 2]. In tropical region, particularly in South-east Asian countries which most of the countries are classified either as tropical rainforest climate or as tropical monsoon climate, the average building energy consumption measured based on Building Energy Index (BEI) is 233 kWh/m^2/yr, where 50 % is used for air-conditioning [3]. This scenario of high energy consumption due to the high usage of air-conditioning system is quite frustrating since many studies revealed that people in tropical climate are more tolerable to higher temperature due to the acclimatization factor [4, 5].

This issue has prompted many energy-conscious researchers to conduct various studies in finding out viable alternatives to air-conditioning system without compromising people's thermal comfort and environment. The studies revealed that one of the most potential strategies is the use of natural ventilation, which is a simple yet effective strategy inherited from the past. Contrary to the air-conditioning system which is often regarded as one of the major causes of global warming, this passive cooling technique of natural ventilation has huge advantages not only in reducing building energy consumption, but also in improving indoor environmental quality [6], reducing sick building syndrome [7, 8] and increasing occupants productivity [9].

Compared to stack ventilation which is based on thermal force, many studies revealed that crossventilation which is depends on wind pressure differential is much more effective natural ventilation strategy in improving indoor thermal environment in the tropical region. The deficiency of the stack ventilation strategy can be associated with several factors such as very low outdoor–indoor temperature differential of the region [10] and inappropriate architectural design like insufficient inlet–outlet opening and unsuitable application of stack ventilation elements [11].

However in the warmer climate and densely built environment of today, the typical strategy of natural cross ventilation is no longer reliable to ensure building occupants comfort at most of the time. The tendency of building designers and occupants to segregate the spaces to suit with specific functions like in a deep plan building and more dense layout of site planning where buildings are placed closely or attached like in the terrace houses have resulted in limited openings for cross flow [12]. Therefore, the more appropriate solution for these undesirable situations could lay on providing effective outlet area at the upper part of the building and the use of heated cavity by solar radiation to enhance stack effect and thus inducing vertical air movement, which this mechanism is called solar induced ventilation strategy.

With some development and advancement of the solar induced ventilation strategies that can maximize the potential of abundant solar radiation in this climate to increase higher indoor–outdoor temperature differential, many recent studies have shown that stack ventilation strategy could be significantly improved and successfully implemented in this region. This includes strategies such as solar wall, solar chimney and solar roof. This book chapter presents the potential and limitations of this solar induced ventilation strategy in this tropical region, particularly in tropical rainforest climate and tropical monsoon climate. The discussion is based on the scientific results from the previous studies, recent innovations and latest technologies associated with such ventilation strategies, as well as remarkable examples of the solar induced ventilation strategies incorporated in contemporarytropical buildings.

4.2 Concept of Stack Ventilation

4.2.1 Stack Ventilation as Natural Ventilation Strategy

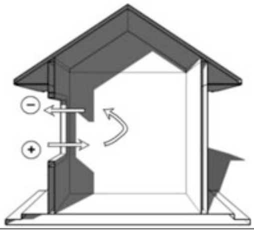
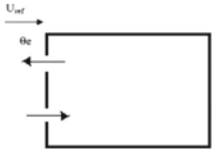
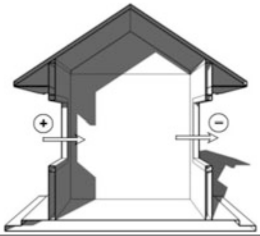
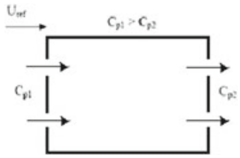
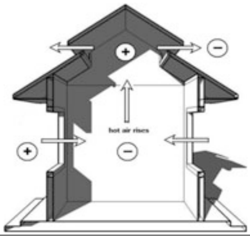
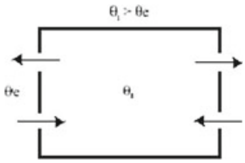
The Oil Embargo during the 1970s has indirectlyreshaped the development of ventilation and cooling systems when its impact has prompted building professionals, including architects and engineers to reinventing passive strategies to ventilate the building for occupants thermal comfort without burning the finite fossil fuels. One of the most significant strategies is by applying natural ventilation, which can be defined as '*the movement of air through openings in a building fabric due to wind or to static pressures created by the indoor–outdoor temperature differences, or to a combination of these acting together*' [13]. Based on this definition of natural ventilation, it is clear that the major driving forces that determine its ventilation rate are wind effect and/or stack effect, which directly will configure its three major forms that can be classified as in Table 4.1.

Single-sided ventilation takes place in the building when air enters (inlet) and exits (outlet) through the same opening of the room. The air movement in this strategy is naturally generated by small difference in building envelope wind pressure, room-scale buoyancy effect and/or turbulence. Due to these factors, this strategy is often regarded as less effective compared to other types of natural ventilation, as stated by some researchers who stressed it to be only work for a depth up to 2.5 times the height of the room [14, 15].

The most common type of natural ventilation is cross ventilation, where air enters the interior spaces through opening in one side (windward) and exit through another opening on the opposite side (leeward). Theoretically, it is revealed that this type of ventilation is effective up to 14 m [14] and 5 times the height of the interior space [15]. Generally, its effectiveness depends on the outdoor air temperature, indoor–outdoor airflow resistance and the size of the inlets and outlets. Due to these factors, it is obvious that the effective cross ventilation needs a room or building form that is exposed to the prevailing wind direction and can provide sufficient size of openings with minimal indoor obstructions between inlet and outlet. These requirements affect its applicability in a deep plan building or building situated in the dense built environment.

In contra, a thermal buoyancy-based ventilation, called as stack ventilationor stack effect, could be a potent strategy for those particular conditions. Stack ventilation can be defined as the vertical movement of air through openings in a building

Table 4.1 Major forms of natural ventilation

Natural ventilation strategy	Typical sectional diagram	Driving force (cross section)
Single-sided ventilation		 Wind effect, stack effect (and/or turbulence)
Crossventilation		 Wind effect
Stack ventilation		 Stack effect

fabric due to pressure differences which varies with height of the building. In this strategy, the hot air that rises due to buoyancy and then extracted out through the upper part of the building will create low-pressure area at the lower building level which in turn induces in colder air from the outside. This principle allows this strategy to be less dependent on outdoor wind condition, thus makes it more effective natural ventilation strategy to be applied in opening-limited buildings like a terrace houses.

4.2.2 Mechanism and Factors Affecting Performance

Basically, the 'stack effect' principle is the main mechanism that generates the stack ventilation, where the air rises due to thermal force. Sectional diagram in Fig. 4.1 below demonstrates this principle, where the lighter and warm air rises upward and exits through the upper openings above the neutral pressure level (NPL), which in turn induces a cooler and heavier outside air entering the building through the lower openings to replace the extracted air.

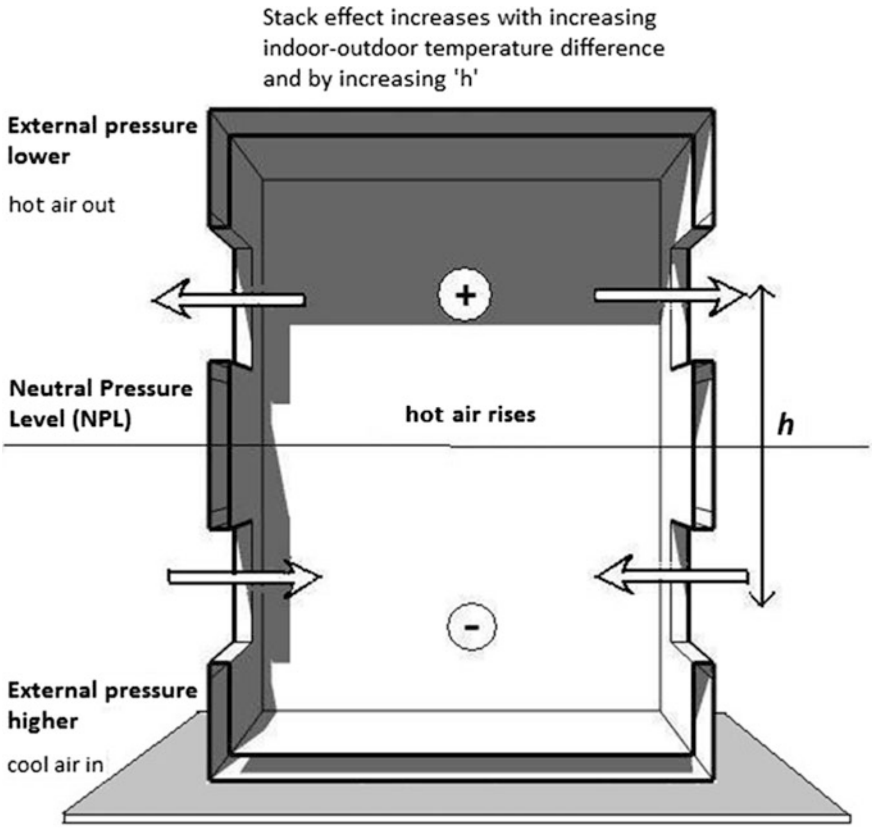


Fig. 4.1 Sectional diagram of stack effect principle

Theoretically, the airflow induced by the stack effect is directly proportional to the effective size or area of the openings, the indoor–outdoor temperature differential and outlet–inlet height differential [13], as formulated in Eq. 4.1.

$$Q = KA\sqrt{h(t_{out} - t_i)} \tag{4.1}$$

where

Q	airflow (m/s)
K	discharge coefficient for the opening (assume K = 0.65 for multiple inlet openings)
A	free area of inlets (m^2)
h	height from mid-point of the inlets to mid-point of the outlets (m)
t_{out}	average temperature of outdoor air (°C)
t_i	average temperature of indoor air (°C)

Based on this principle, it is clear that the temperature differential between indoor and outdoor spaces, the openings size (inlets and outlets), and the height of the spaces are major parameters that will determine the effectiveness of the stack ventilation or stack effect strategy. The following subsections further describe these parameters.

4.2.2.1 The Temperature Difference Between the Exterior and Interior Spaces

Generally, the stack ventilationwill only work if there is sufficient temperature differential between outdoor and indoor spaces, where the air temperature of the latter should be cooler than the former. Specifically, the air temperature difference between exterior and interior spaces should be at least 1.7 °C to generate upward airflow due to the pressure differences, while a higher temperature difference could drive more effective airflow and cooling [16]. This requisite looks can easily be achieved in cold or temperate climate, but not for the tropics where the temperature differential between outdoor–indoor is very low at most of the time, which has limited its applicability in this region. In fact, during the afternoon when cooling is most needed by the building occupants, the exterior temperature is observed to be usually higher than the interior, which makes its effect almost insignificant in this type of climate.

4.2.2.2 The Size of Inlets and Outlets

The size of inlets and outlets is also one of the factors that determine the ventilation rate of the stack ventilation, where the maximum airflow rate occurs when the inlet size (area) is equal to the size of the outlets [16]. If the outlet opening is used in combination with the stack duct, the free area of the former is recommended to be twice the free area of the latter in order to maximize the airflow. Moreover, the terminal should also be raised above the roof ridge or any obstruction to avoid it from the more turbulent zone resulted from the passing wind over a building [16]. In addition, the stack outlet should also be designed by considering the appropriate position of the opening since it can reduce or even reverse the impact of the stack flow. Due to this factor, it is suggested that the outlet or the air terminal is opened on all sides to ensure that in windy conditions, wind regardless of direction can assist the stack effect [16].

4.2.2.3 The Height of the Space

The effectiveness of natural stack ventilation is also influenced by the height of the space, particularly the vertical distance between the outlet and the inlet. The increasing height between the lower inlet and the higher outlet positions will increase the pressure difference, which in turn can shift the NPL, thus resulting in larger effects of buoyancy-driven ventilation. Since ages, several architectural elements such as raised stack, chimneys and tall room are constructed by maximizing this principle to induce higher vertical air movement in various types of buildings.

The appropriate position or height of the openings is also vital to ensure the maximum cooling effect resulted from the air movement can be experienced by the occupants of the building. Theoretically, it is recommended that the openings should be placed within the height of the occupied zone, which is between 0.3 and 1.8 m above the floor [11].

4.3 Potential and Constraints of Stack Ventilation in Tropical Climate

Tropical rainforest climate (Af) and tropical monsoon climate (Am) are two types from three subtypes of tropical climate according to Köppen climate classification. Tropical rainforest climate (Af) which lies between 5 and 10° north and south of the equator can be characterized by consistently high temperature, abundant sunshine and heavy rainfall throughout the year, with the annual average precipitation recorded is usually higher than 1500 mm. The wind velocity is generally low with the calm condition of less than 0.3 m/s occurred at high percentage of time, resulted from minimal temperature differences. However, thunderstorm with heavy precipitation occurs frequently throughout the region.

Sharing many similar characteristic with the tropical rainforest climate, the tropical monsoon climate which lies within 10–25° north and south of the equator also experiences hot temperature throughout the year and received abundant rainfall in the year, with yearly precipitation ranges between 1500 and 4000 mm. However, it has a more pronounce short dry season and wet season, with abundant rainfall is more concentrated during the high-sun season.

Some examples of the countries which experience tropical rainforest climate are Malaysia, Singapore, Brunei and Indonesia, while Thailand, Myanmar, Bangladesh, Indonesia's Central Java and most parts of Philippines are some countries or areas which are classified to experience tropical monsoon climate. In brief, the characteristic of these both subtypes of tropical climate can be described as follows:

Temperature

The tropical rainforest climate is characterized by no distinct dry season, and uniformly high ambient air temperature all year round with monthly temperature variations is usually less than 3 °C. The air temperature ranges between 27 and 32 °C during the day with mean maximum of about 32 °C, while the night air temperature ranges between 21 and 27 °C with mean minimum of about 22 °C. This small minimum–maximum temperature differential results in the narrow daily diurnal temperature between 5 and 12 °C. Slightly difference from the tropical rainforest climate, the tropical monsoon climate experiences short dry season with the highest temperature is often recorded just before rainy season. The monthly temperatures for all months are above 18 °C in average while monthly temperature variations are between 2 and 6 °C [17].

Relative Humidity
The relative humidity (RH) level in most parts of this climate region is almost constantly high at about 75 % in average throughout the year, but varies from 55 % to almost 100 %. Usually, the lowest values of RH occurred during the afternoon between 1.00 pm and 5.00 pm, which correlates with the highest outdoor air temperature. This condition occurred due to the fact that the increment of dry bulb temperature (DBT) would enhance the ability of air to hold higher amount of moisture, which resulted in decreasing level of RH at the same time of increasing level of ambient air temperature.

Solar Radiation
Solar radiation in tropical climate is partly scatted by cloud cover but remains strong. For example, the intensity of solar radiation in Malaysia which is one of the hot–humid climate countries is generally high and consistent throughout the year in which the recorded value is between 1419 and 1622 kWh/m^2/year [18] and the mean global radiation between 10.5 and 19.0 Mj/m^2/day for most parts of the country [19]. Usually, the continuous presence of cloud makes it ground to receive diffuse solar radiation rather than direct radiation which resulted in uncomfortable sky glare problem. This considerably high cloudiness of 5/8 in average not only restricts the sunlight significantly and filters the solar radiation, but also minimizes outgoing radiation at night, thus making a hotter night condition.

The review on the tropical climate conditions revealed that it is quite a challenge to provide occupants thermal comfort in the building since the ambient air temperature of over 30 °C and RH surpasses 60 % at most of the daytime are fell beyond most definitions of thermal comfort limits. This review leads to the conclusions that neither cross ventilation nor natural stack ventilationis applicable and reliable to provide sufficient ventilation to ensure occupants comfort in this type of climate.

The low outdoor wind velocity and high percentage of calm condition has been a major constraint for the effective use of the conventional wind-driven cross ventilation while the low indoor–outdoor temperature differential has demolished the potential of natural stack ventilation role which is based on stack effect to induce upward air movement in the absent of wind. However, with the abundant solar radiation available in this climate, the conventional strategy of natural stack ventilation could be significantly improved if the high solar radiation can be fully exploited to increase indoor–outdoor temperature differential by heating the building cavities and thus increasing the stack effect. Since the ventilation performance of this solar induced strategy increased with the increment of solar radiation received, it offers huge potential to be used as a natural ventilation strategy in the tropical building, especially during the afternoon when passive cooling is most needed in the building.

4.4 Solar Induced Ventilation: Types and Applications in Hot–Humid Tropical Building

Since centuries, people all over the world have developed many strategies in harnessing free solar energy to improve the performance of stack effect, or natural stack ventilation. This strategy which is classified as solar induced ventilation strategy relies upon the heating of the building fabric by solar radiation resulting into greater temperature difference to increase stack effect [20]. Basically, there are three building features which are usually applied in the building that have been developed based on this strategy, i.e. solar wall (Trombe wall), solar chimney and solar roof [15].

4.4.1 Solar Wall

Solar wall is one of the solar induced ventilation strategies which is usually associated with passive heating rather than cooling, particularly the Trombe wall which is equipped with vents at the lower and upper parts of the wall for the air circulation (Fig. 4.2a). Basically, it is a thermal storage wall generally made of thick concrete or masonry wall with heat-absorbing colour, an air gap and with a single or double layer glass on the exterior. With these elements and configuration, the trapped heat within the air gap resulted from the solar radiation will be transferred slowly passes through the massive wall to heat the interior, while the vents ensure that the colder air induced from the lower part of the building is heated first in the air gap before the hotter air will be channelled back to the interior through the upper vent.

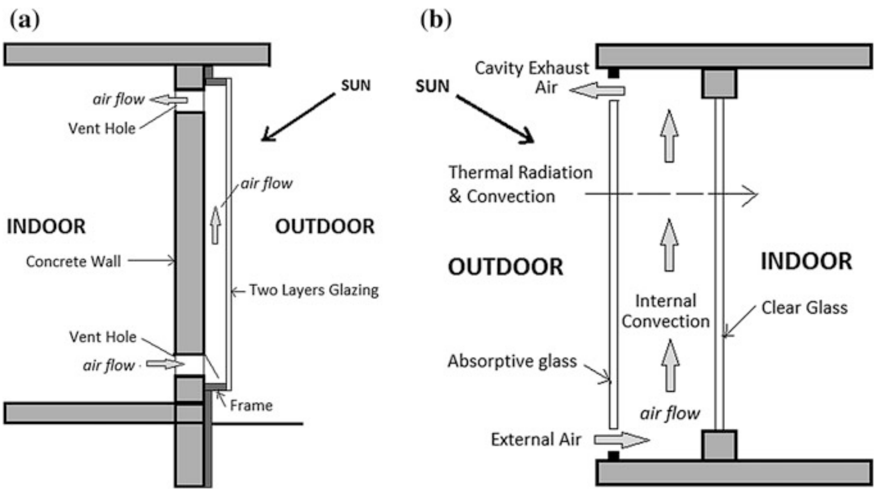


Fig. 4.2 Heat transfer and air movement in (**a**) Trombe wall with vents (**b**) double-skin facade

In tropical climate of Thailand, a study done by Hirunlabh et al. [21] on the effectiveness of a metallic solar wall discovered that the solar wall encompassed of zinc plate, microfibre and plywood was capable to induce maximum 1.65 ACH of ventilation rate in the model room. In terms of air velocity, Chantawong et al. [22] revealed that the prototype glazed solar chimney wall was able to induce air movement of about 0.07 to 1.4 m/s. With the height of less than 1 m, the solar wall tested is considered suitable to be incorporated to the window design. In a more recent study, Punyasompun et al. [23] showed that the solar induced ventilation could also be an effective façade element for multi-storey tropical buildingin improving indoor thermal environment when its application in Thailand had succeeded to reduce indoor air temperature by about 4–5 °C as compared to the multi-storey building without solar wall.

In hot humid tropical climate where passive cooling is more desirable rather than heating, the more preferred strategy which also uses solar radiation to induce stack ventilationis by incorporating the double-skin façade (DSF), as shown in Fig. 4.2b. The DSF is an element of building which comprised of an outer and inner glazed skin to provide both ventilation and daylight for the building, and at the same time lessening the amount of heat transmitted into the interiors. In this strategy, air in the cavity, which is the intermediate space between the glazes is heated by solar radiation, which in turn significantly enhances the stack effect to remove hot air out through the upper outlet area.

Nowadays, a plethora of contemporary tropical buildings like in South-east Asian countries has incorporated this type of solar induced ventilation strategy in their design, which the main intention is to reduce the amount of heat from entering the building as well as for ventilation and daylighting purposes. This includes buildings like Energy Complex and SCG 100th Year Building in Thailand, Allianz Tower in Indonesia, and National Library Building, Fusionopolis, CapitaGreen and Nanyang Technological University (NTU) School of Art, Design and Media (ADM) in Singapore, as shown in Fig. 4.3a.

In CapitaGreen building located in Singapore (Fig. 4.3b), the incorporation of high-rise vegetated façade within double skin is not only benefit the building in terms of environmental and psychological aspects, but also directly provides it

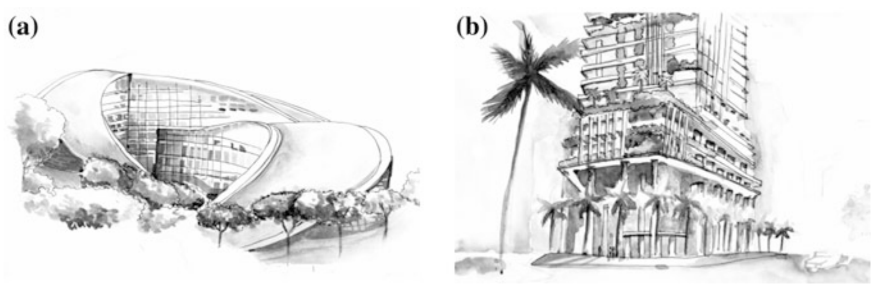


Fig. 4.3 Contemporary Singapore buildings with double-skin facades applied (**a**) The NTU School of Art, Design, and Media (**b**) CapitaGreen building

natural solar shading. This strategy is considered significant in reducing solar heat gain and overheating problem usually associated with the implementation of DSF in tropical climate.

Some examples of the contemporary buildings in Malaysia that have been designed with double-skin facade are SIDC Headquarters and KETTHA LEO Building in Putrajaya, PTM ZEO Building in Selangor and Tribe Condominium in Bukit Bintang, Kuala Lumpur. In the eight-storey building of The Securities Commission of Malaysia built in 1998 in Kuala Lumpur, vertical and horizontal shading devices which are placed within double layers of glass has succeeded to provide sufficient transparency for daylight and at the same time was able to minimize the adverse effect of solar heat and glare. In order to maximize its function in terms of ventilation, the DSF of the building is designed as a ventilated air gap walkway which is equipped with air exhaust van at the upper part to extract hot air and lessening the amount of heat from absorbing into the building (Fig. 4.4).

4.4.2 Solar Chimney

Since ages, solar chimney has been used in various types of vernacular architecture worldwide to enhance natural ventilation, making it to be one of the most common solar induced ventilation strategies hitherto. In this strategy, the air inside the chimney is heated due to the absorption of solar radiation by its glazing surface, which resulted in higher pressure difference between the outlet and inlet of the

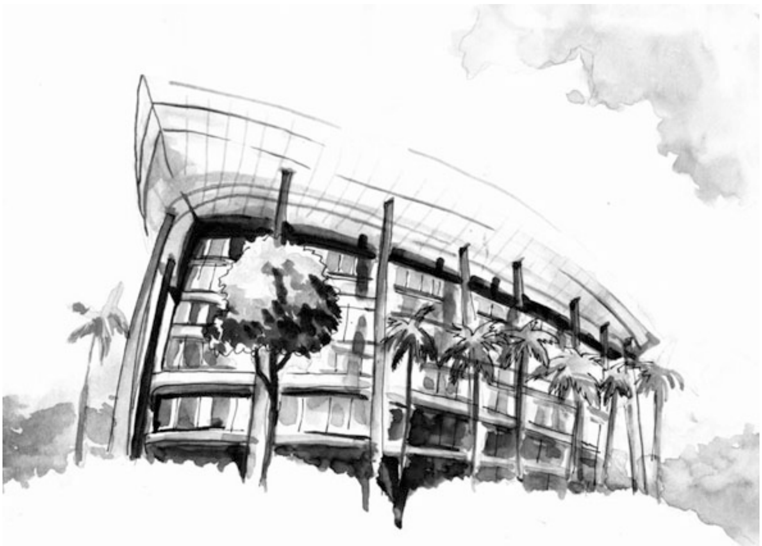


Fig. 4.4 SIDC Headquarters, Malaysia

chimney, thus enhancing the upward air movement or stack effect significantly [20, 24, 25]. This principle clearly demonstrates its synergy to enhance ventilation rate at the time when ambient air is getting hotter. The effectiveness of the solar chimney to remove hot air out could also be enhanced by its physical feature of having a free outlet area or air terminal positioned high above the roof which permits higher outdoor wind velocity to pass through and produces a negative pressure to induce the indoor air.

In humid tropics of Thailand, Khedari et al. [26] revealed that the solar chimney could induce 8–15 ACH ventilation rates and had generated airflow of about 0.04 m/s at occupied zone (1 m above the floor level). In a more recent study, Nugroho [27] revealed that the prototype solar chimney applied at single-storey terrace house under Malaysian climate had succeeded to increase air velocity up to 0.7 m/s.

Although the application of solar chimney is still not widespread in the tropics, but recently there are some examples of the contemporary tropical buildings which have started to incorporate this solar induced ventilation strategy in their design. For example, a series of solar chimneys have been placed at the top of the roof of the zero-energy building (ZEB) at Building Construction Authority Academy in Singapore to enhance stack effect and thus reducing energy consumption used for the ventilation system (Fig. 4.5).

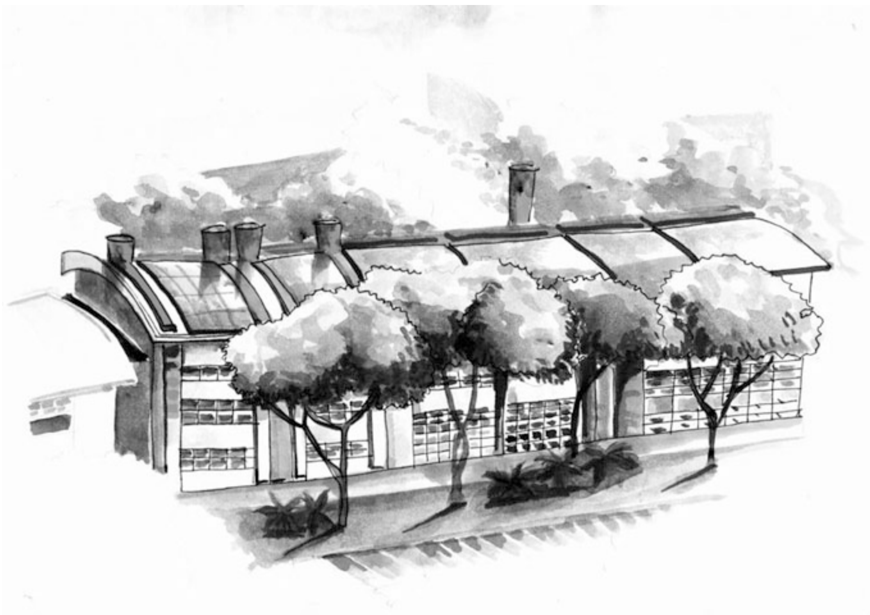


Fig. 4.5 Incorporation of solar chimneys on zero-energy building (ZEB), Singapore, to enhance stack effect and extract out hot indoor air

This ZEO building which is retrofitted with some green building elements has used red-coloured solar chimneys to enhance stack ventilation in its classrooms and lecture hall by maximizing the usage of heat produced by roof-mounted solar panels. In its design, the 300 mm cavity provided between the metal roof and the solar panels is not only important in ensuring the efficiency of the solar panels during its operation, but also vital to produce significant heat that can enhance buoyancy effect, thus inducing upward movement of warm indoor air to enter the air channel before extracting it out through the air gap and solar chimneys.

4.4.3 Solar Roof

Solar roof also called as roof solar collector (RSC) or double roof is one of the solar induced ventilation strategies which is usually incorporated in buildings located in large solar altitude area. In this strategy, the large sloping roof is used to harness free solar energy by absorbing solar radiation to heat the cavity between inner and outer roofs, as shown in Fig. 4.6. This heated cavity will produce greater negative pressure to induce upward airflow from the occupied space then remove it out through its upper outlet area. A study by Khedari et al. [28] under the tropics of Thailand showed that the conventional solar roof or RSC was capable to produce ventilation rate of about 0.08–0.15 m^3/s. This rate, however, could be increased with the application of the RSC prototype configuration when this subsequent study revealed that the RSC with 14 cm air gap succeeded to induce maximum air change rate of 4 ACH in Thailand building [29, 30].

Following these studies, several configurations of solar roof collector were developed and tested under Thailand climate. This includes a study on solar

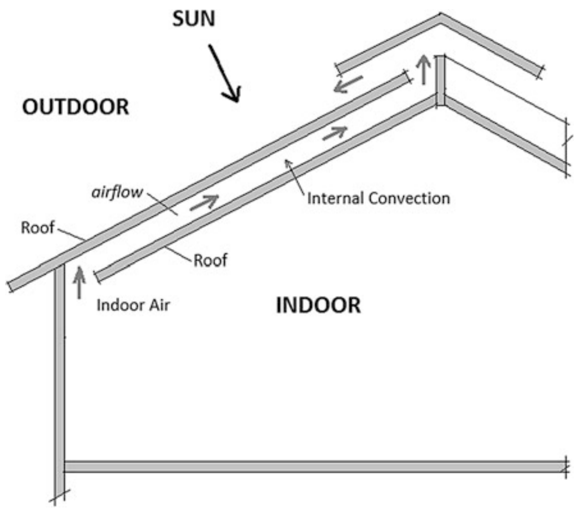


Fig. 4.6 Sectional diagram of typical solar roof

collector resembled the traditional Thai roof where such configuration was able to induce airflow rate up to 0.07 m^3/s. Another study by Puangsombut et al. [31] on solar collector which utilized a radiant barrier at its lower plate succeeded to reduce the heat transfer through it by about 50 % and increase airflow rate by 40 to 50 %.

On the other hand, Chungloo and Limmeechokchai [32] revealed that the solar collector equipped with a wetted roof is significant to reduce indoor air temperature by 2 to 6.2 °C as compared to conventional RSC. In a more recent study on a prototype roof solar collector combined with cool ceiling, the results showed that such combination was capable to decrease ceiling temperature up to 4 °C and reduce room air temperature by 0.5 to 0.7 °C [33]. In another study done in Brunei, Yakup and Malik [34] found that the tilt angle of the RSC should be altered according to the monthly averaged optimum tilt angle to increase its ability in receiving maximum amount of solar radiation. Such strategy could achieve at least 5 % a yearly gain in solar radiation as compared to the typical placement of RSC on horizontal surface.

In effort to enhance the performance of RSC, several prototypes that combine the RSC with other stack ventilation strategies such as vertical stack, solar wall and solar chimney have been developed and tested. A study by Yusoff et al. [35] in Malaysia showed that a RSC combined with vertical stack achieved to improve the stack ventilation, both in overcast sky and semi-clear sky conditions, when the highest temperature difference between the air inside the stack and the outdoor air recorded was 6.2 and 9.9 °C, respectively. In Thailand, Khedari et al. [36] showed that the application of the RSC combined with Trombe wall in an air-conditional building was able to save about 10–20 % daily energy consumption when such application significantly has reduced the amount of heat transfer through the roof and wall.

4.5 Conclusion

Literature surveys revealed that the natural stack ventilation, or stack effect could be a significant ventilation strategy in inducing upward airflow and extract hot stale air from the upper part of the building, especially when the air movement is not dominated by the cross ventilation reaching 1.8 m/s [37]. For contemporary buildings, this vital role of the stack ventilation strategy is more substantial in certain situations such as buildings located in densely built environment and deep plan buildings where the cross ventilation has restricted functions. However, since the effectiveness of this strategy is very dependent on the sizes of inlet and outlet openings, the stack height and the differences between indoor and outdoor temperature, its effect in tropical building is always considered negligible, especially for low-rise building.

These constraints have prompted several researchers to develop some solar induced ventilation strategies such as solar roof, solar chimney and solar wall to maximize abundant solar radiation available in this climate region to enhance the stack effect, which some studies showed that the prototype strategies was able to either improve indoor thermal environment, increase air movement and ventilation rate or minimize cooling load which in turn reducing the building energy consumption on the whole. From the literatures, it is clear that contrary with natural stack ventilation which usually can only provide weak stack effect due to ensure the indoor air temperature is as low as possible, all solar induced ventilation strategies discussed above offer more promising outcomes since they are innovated to take full advantage of solar gains and are remote from the occupied space. This advantage enriches its potential to be applied in contemporary buildings in the tropics. However, the results of the studies showed that although the strategies could be a potential strategy to boost natural stack effect, the low rate of air movement created by this strategy in the occupied zone has lessened its reliability and applicability to be adopted in the contemporary buildings where comfortable thermal condition is favoured. Moreover, the complexity issue and considerably high construction cost have constrained its wide application, especially in residential buildings.

However, recently there are several contemporary buildings in tropical region which have been designed with the incorporation of solar induced ventilation strategies such as double-skin face and solar chimney to increase natural ventilation and thus reducing energy consumption in the building. Although the ventilation performance of such solar induced ventilation strategies is not specifically investigated in the real occupied building, but it shows that the strategy is now gaining a good perception from the designers which can indirectly contribute to the widespread use of the strategy in this region that may result in the lower cost of the related technology. Moreover, with the continuous development of the strategy, it is expected that several prototypes of the solar induced ventilation strategy that are more applicable and reliable to be used in this tropical climate and can ensure occupants thermal comfort could be developed in the near future. The rationale for this expectation is based on the general principle and the strength of the solar induced ventilation itself, which is its capability to self-balance; the hotter the day, the hotter the solar air heat collector and the faster the air movement [24]. This advantage could be a main basis for developing any solar induced ventilation strategy to be incorporated in various building types in the tropics, where the solar radiation is abundant.

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Chapter 5
Insights to Current Lighting Technologies and Low Environmental Impact Artificial Lighting

Xiaofeng Zheng

Abstract This chapter aims to review the previous lighting technologies and discuss the impact of lighting design and user behaviour to the energy consumption of lighting as well as life cycle assessment of luminaires. Energy for lighting can consume between 31 % (in retail store applications) and 60 % (in educational settings) of an organization's electricity budget. The price of electricity has never stopped its rising trend due to the global issue of energy scarcity. Therefore, a lot of efforts have been made in seeking ways to cut the electricity bill by reducing the energy consumption of lighting system and operating more efficiently. Insight will be shed onto the status of energy consumption by lighting, current lighting technologies, design and control, and the life cycle assessment of luminaires. Finally, a less resource depriving and low energy consuming way of using artificial lighting is proposed.

Keywords Lighting · Energy consumption · Luminaire · Life cycle assessment

5.1 Status of Lighting Energy Consumption

Concluded by a study from the International Energy Agency (IEA) which has conducted the first global survey of lighting uses and costs, a global switch to efficient lighting systems would trim the world's electricity bill by nearly 10 %. Lighting is a major source of electricity consumption as about 19 % of global electricity generation is taken for lighting [1], which is more than that produced by hydro or nuclear stations, and about the same amount produced from natural gas. The carbon dioxide produced by generating the electricity for lighting use equals to 70 % of global emissions from passenger vehicles, and three times more than emissions from aviation. Lighting has a substantial impact on the environment: the

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commercial sector counts more than 25 % of energy consumption in EU for the lighting sector [2].

Developed a century and a quarter ago by luminaries including Sir Joseph Swan and Thomas Edison, the incandescent bulb has been the one producing almost half of the light used in homes around the world. However, they are very inefficient because only about 5 % of the received energy is converted into light. The rest of the energy is wasted by escaping into the ambient. Currently, the biggest consumer is the fluorescent tube, which accounts for 43 % of the electricity used for lighting in the commercial and public sector buildings. The efficiency of fluorescent tube varies widely from 15 to 60 %. Meanwhile, a significant proportion of the world's population has no access to electric lighting at all, replying on burning expensive and inefficient fuel which produces poor light quality and contributes to respiratory disease.

According to the research by IEA, setting up a comprehensive set of policies is in urgent need to introduce lighting measures into building codes at national level. Such codes could advocate or mandate the use of lighting technologies which deliver high energy efficiency. In domestic and service sectors, the electricity consumption for lighting accounts for 18 and 21 % in 2010, respectively [3, 4]. The energy consumed by lighting in buildings is a major contributor to carbon emissions, accounting for 20–40 % of the total building energy consumption [5, 6].

Service sector includes public administration, commercial, agriculture and miscellaneous. The space for cutting the carbon footprint caused by the energy consumption in lighting sector is big which leaves us a lot to do [4]. Comprehensively reviewing the factors that influence the energy consumption of lighting, the major ones that affect the energy consumption significantly are concluded and they include the lighting technologies, control methods and user awareness. The following section will introduce a possible way of sustainable lighting to cut the carbon footprint associated with lighting.

5.2 Current Lighting Technologies

The comparison of different lighting technologies should be based on capital cost of the lamp, conversion efficiency, lighting performance, lamp life, various depreciation factors for light output as the lamp ages, as well as labour cost to replace lamps.

5.2.1 Incandescent

The incandescent light bulb produces light by heating a filament wire to a high temperature until it glows. The hot filament is protected from oxidation in the air with a glass enclosure that is filled with inert gas or evacuated. In a halogen lamp, filament evaporation is prevented by a chemical process that redeposits metal vapour onto the filament to extend its lifespan. The light bulb is supplied with electrical current by feed-through terminals or wires embedded in the glass. Most bulbs are used in a socket which provides mechanical support and electrical connections. Incandescent bulbs are manufactured in a wide range of sizes, light output and voltage ratings, from 1.5 volts to about 300 volts. They require no external regulating equipment, have low manufacturing costs, and work equally well on either alternating current or direct current. As a result, the incandescent lamp is widely used for household and commercial lighting, portable lighting such as table lamps, car headlamps, flashlights and decorative/advertising lighting.

Incandescent bulbs are highly wasteful because less than 10 % of the consumed energy is converted into visible light, with the remaining energy converted into heat, although some applications of the incandescent bulb, including incubators, brooding boxes for poultry, heat lights for reptile tanks, infrared heating for industrial heating and drying processes, deliberately use the heat generated by the filament. However, in many circumstances, waste heat can significantly increase the energy consumed by air conditioning. Incandescent light bulbs are gradually being replaced in many applications by other types of electric lights, such as fluorescent lamps, compact fluorescent lamps (CFL), cold cathode fluorescent lamps (CCFL), high-intensity discharge lamps, and light-emitting diodes (LEDs).

5.2.2 *High-Intensity Discharge Lamp*

High-intensity discharge (HID) lamps are a type of electrical gas-discharge lamp which produce light by means of an electric arc between tungsten electrodes enclosed in a translucent or transparent fused quartz or fused alumina arc tube. The tube is filled with both gas and metal salts, facilitating the arc's initial strike. It heats and evaporates the metal salts forming plasma once the arc is started. The plasma increases the intensity of lighting produced by the arc and reduces its power consumption. High-intensity discharge lamps make more visible lighting per unit of electric power than fluorescent and incandescent lamps because the conversion efficiency of electric power to visible light is higher.

The high-intensity discharge lamps have various types, depending on the desired characteristics of light intensity, correlated colour temperature, colour rendering index (CRI), energy efficiency and lifespan. They include as follows:

- Mercury-vapour lamps
- Metal halide lamps
- Ceramic metal halide lamps
- Sodium-vapour lamps
- Xenon short-arc lamps

Mercury-vapour lamps were the first commercialized HID lamps, which uses an electric arc through mercury vapour to produce light. It originally produced a bluish-green light, but more recent versions can produce clear white light. Compared to incandescent and most fluorescent lights, it is more energy efficient with luminous efficacies lying in the range of 35–65 lumens/watt and lifetime at about 24,000 h [7]. Usually, they are used for large area overhead lighting, such as in factories, warehouses and sports arenas as well as for streetlights. At the end of life, mercury-vapour lamps burn out as the burner electrodes wear, increasing the arc gap. In consequence, the lumen output depreciates obviously, which thanks to the deposition of emitter on the arc tube, reducing the light output.

A metal halide lamp is an electric lighting that produces lighting by an electric arc through a gaseous mixture of mercury vapour and metal halides, which are compounds of metals with bromine or iodine. It consists of a small fused quartz or ceramic arc tube which contains gases and arc, enclosed inside a glass bulb with a coating to filter out produced ultraviolet light. It belongs to the HID family of gas-discharge lamps. It operates under high pressure (4–20 atmospheres) [9] with the luminous efficacy at around 75–100 lumens per watt [8], which is twice the efficiency of mercury-vapour lights and 3–5 times that of incandescent lights [9]. The lamp produces an intense white light with the lifespan lying in the range of 6000–15,000 h, a little shorter than mercury lamps. Usually, they are used for wide-area overhead lighting of commercial, industrial and public spaces as well as security lighting and automotive lighting.

The ceramic metal halide lamp is a variation of the metal halide lamp, differing itself by the ceramic tube which contains the discharge. The ceramic container is usually made of sintered alumina, similar to what has been used in the high-pressure sodium lamp. The ceramic container, filled with mercury, argon and metal halide salts, can operate at high temperature, exceeding 900 °C. The advantage of ceramic tube is due to the avoidance of depleting the tube inner wall by the penetration of metal ions to the silica. The sodium-vapour lamp, including low pressure and high pressure, uses sodium in an excited state to produce light. Low-pressure sodium lamp produces yellow light.

Low-pressure sodium lamp has a borosilicate glass gas-discharge tube containing solid sodium, a small amount of neon and argon gas in a penning mixture. It emits a dim red/pink light to warm the sodium metal and turns into the common bright yellow light within a few minutes as the sodium metal vapourizes. Low-pressure sodium lamp is considered to be the most efficient electrically powered light source when measured for photopic lighting conditions up to 200 lm/W, because the wavelength of the light output locates near the peak sensitivity of the human eye. When it approaches to the end of life, the voltage that is necessary for maintaining the arc rises to exceed the voltage provided by the electrical ballast. This makes the lamp overheated and go out until the lamp cools down again; this phenomenon is called cycling existed in many types of HID lamps.

The xenon arc lamp is a specialized type of gas-discharge lamp, an electric light that produces light by passing electricity through ionized xenon gas at high pressure. It produces a bright white light that closely mimics natural sunlight. It is usually used in movie projectors in theatres, in search lights and for specialized uses in industry and research to simulate sunlight. There are two types of lamps which include pure xenon and xenon–mercury, which contain only xenon gas and the mixture of xenon gas and a small amount of mercury metal, respectively. In pure xenon lamp, the majority of the light is generated within a tiny cloud of plasma situated where the electron stream leaves the face of the cathode. The light generation volume is cone-shaped and the luminous intensity falls off exponentially moving from cathode to anode. Electrons passing through the plasma cloud strike the anode, causing it to heat.

In xenon–mercury short-arc lamps, the majority of the light is generated in a pinpoint-sized cloud of plasma situated at the tip of each electrode. The light generation volume is shaped like two intersecting cones and the luminous intensity falls off exponentially moving towards the centre of the lamp. It has a bluish-white spectrum and extremely high UV output. They are primarily used for UV curing applications, sterilizing objects and generating ozone, operating at low-voltage, high-current DC devices with a negative temperature coefficient. However, they require a high-voltage pulse in the range of 20–50 kV to strike the lamp with the assistance of a well-regulated DC power source.

5.2.3 Compact Fluorescent Lamp (CFL)

Compared to the traditional incandescent lamp, compact fluorescent lamp (CFL, also called energy-saving light) consumes less electrical power to supply the same amount of light with 8 to 15 times longer lifespan [10]. It is designed to replace the incandescent lamp as some types fit into the same light fixtures used by incandescent lamps originally. The tube of the lamp is curved or folded into the space of an incandescent with compact electronic ballast in the base of the lamp. Generally, a CFL costs more than an incandescent lamp but can save over five times cost for electricity usage in its lifetime compared with the incandescent lamp [11]. Due to the ability of reducing electric consumption, many organizations have undertaken measures to encourage the adoption of CFLs. Some electric utilities and local governments have subsidized CFLs or provided them free to customers as a means of reducing electricity demand. For a given light output, CFLs use between one-fifth and one-quarter of the power of an equivalent incandescent lamp. Suggested by the Alliance for Climate Protection, the CFL has been regarded as one of the simplest and quickest ways for a household or business to become more energy efficient. In the past decade, the fabrication process can expose the workers into poisonous environment because of long-time exposure to the environment containing mercury [12].

5.2.4 Light-Emitting Diodes

The key part of LED lamp is a solid-state semiconductor device like a regular diode, in the simplest form of semiconductor device which conducts electricity in only one direction with a varying capacity. Most semiconductors such as transistors and diodes are made of a poor conductor that has impurities (atoms of a different material—usually arsenic) added to it, which is called doping. The LED consists of a chip of semiconducting material doped with impurities to create a P–N junction. As in other diodes, current flows easily from the p-type (as it has been positively charged with extra particles) to the n-type (as it has been negatively charged with extra particles), but not in the reverse direction. Charge carriers—electrons and holes—flow into the junction from electrodes with different voltages. When an electron meets a hole, it falls into a lower energy level and releases energy in the form of a photon.

In LEDs, the semiconductor material is typically aluminium–gallium–arsenide (AlGaAs), in which all of the atoms bond perfectly together without leaving any free electron to conduct electric current. In the doped material, additional atoms change the balance of the conductivity in the material, either adding free electrons, or creating holes where electrons can flow, in response to an electrical current. Either of these additions makes the material electrically more conductive. An LED consists of a small chip of semiconductor material—often less than 1 mm $\times$ 1 mm doped with impurities to create a P–N-type junction.

The colour of the emitted light depends on the band gap (difference in energy levels) of the semiconductor materials forming the P–N junction. The types of materials used for LEDs have a band gap which can produce light varying from near-infrared, through visible, to near-ultraviolet light depending on the design of the LED. The small LED chip is encapsulated in a plastic casing along with the leads and sometimes other components such a reflector or a heat sink.

Regular LEDs produce a small amount of heat during operation, but the leads are usually enough to keep the die at a reasonable operating temperature. Higher output LEDs, and especially white-light LEDs produce larger amounts of heat, thus proper thermal management and heat sinking is necessary. If the LEDs were to operate at the maximum design temperature, the sensitive junction could become overheated and the LED will be broken down.

An LED power supply serves the same function as the ballast in a magnetic induction light. It takes the incoming mains power, rectifies it to DC, smoothes and filters the DC power, and then uses electronics to provide a constant, direct current, to the LEDs power supply. LEDs are current-sensitive devices where brightness is proportional to the applied current within the design specifications of the LED. If too much current is used to the LED, the sensitive junction on the die will be destroyed and the LED will fail. A limited or constantly regulated current must be used to achieve a normal operation of LED.

There are no semiconductor materials for LEDs which emit white light directly. One can combine red, green and blue LED chips into a single encapsulation (RGB

LED) by turning on each at full power. Many shades of "white" can be produced by adjusting the relative brightness of R, G and B emitters. However, this is not an efficient process as additional electronics are required.

For lighting applications, an LED that possesses the maximum amount of white light output is desirable. So manufacturers came up with phosphor-coated LEDs, which involves coating the interior (or exterior) with different types of phosphors to produce white light. These LEDs are technically called phosphor-based LEDs but mostly referred as white LEDs.

In a phosphor-coated LED (mostly single blue LED), a portion of the blue light emitted by the LED die is up-converted by the phosphor such that it is transformed from shorter wavelengths to longer wavelengths. Some of the blue light travels through the phosphors, mixing with the up-converted light emitted by the phosphors to provide "white" light output. Depending on the colour emitted by the LED die, different phosphors can be used to produce different shades of white and thus different perceived colour temperatures. A number of layers of phosphors are usually applied to broaden the emitted spectrum, which in turn effectively increases the CRI of the white LED.

These LEDs have a lower efficiency than regular LEDs due to the heat produced by the up-conversion process in the phosphors, and also due to other phosphor-related degradation issues. The phosphor coating method is still the most popular technique for manufacturing high output white LEDs. The majority of high-intensity white LEDs presently on the market use phosphor coating because it is cheaper and simpler to design and produce than using complex RGB LED-based system. LED lamps could be a cost-effective option for lighting a home or office space because of their very long lifetimes. The use of LEDs as a replacement for conventional lighting system is currently hampered by the high cost. The high initial cost of LED is due to the expensive sapphire substrate which must be coupled with a mirror-like collector to reflect light that would otherwise be wasted.

However, the price of using LED outweighs the initial high cost of LED lamps. A building's carbon footprint from lighting can be reduced by 85 % by exchanging all incandescent bulbs for new LEDs. Eric [13] introduced an example of using LED lamps to light a new factory interior and exterior in Sentry Equipment Corporation in Oconomowoc, Wisconsin, USA. Despite the initial cost of LED lamps was three times more than a traditional mix of incandescent and fluorescent lamps, the lower consumption of electricity by LED lamps enables the factory to recover the extra cost within two years via electricity savings. Due to the much longer lifespan of LED, the lamps should not need to be replaced for 20 years. The Indian IT company iGate spent about US$80,000 to light 5300 m^2 of office space with LED lamps expecting to fully recover the cost within 5 years [14]. It is also used to light roads. An example is given by a new motorway inaugurated in Aveior, Portugal, which included the first European public LED-based lighting highway [15]. LED lamps have also been used for a number of demonstration projects for outdoor lighting and LED street lights [16, 17].

5.2.5 Magnetic Induction Lamps

Magnetic induction lamps are basically fluorescent lamps with electromagnets wrapped around a part of the tube, or inserted inside the lamp. In external inductor lamps, high-frequency energy, from the ballast, is sent through wires, which are wrapped in a coil around the ferrite inductors on the outside of the glass tube, creating a power magnet. The induction coil produces a very strong magnetic field which travels through the glass and excites the mercury atoms in the interior. The mercury atoms are provided by the amalgam (a solid form of mercury). The excited mercury atoms emit UV light and, just as in a fluorescent tube, the UV light is down-converted to visible light by the phosphor coating on the inside of the tube. The glass walls of the lamp prevent the emission of the UV light as ordinary glass blocks UV radiation in the 253.7 and 185 nm range.

The induction system can be considered as a type of transformer where the inductor outside the glass envelope acts as the primary coil. The high-frequency magnetic field from the inductor is coupled to the metallic mercury ions causing their electrons to reach an excited state. When the electrons revert to the ground state, photons of UV light are emitted which excites the phosphor coating to emit visible light.

The external inductor lamps have the advantage that the heat generated by the induction coil assemblies is external to the tube and can be easily dissipated to the ambient environment through the combination of radiation convection and conduction. The external inductor design lends itself to higher power output lamp designs which can be rectangular or round. In the internal inductor lamps, the heat generated by the induction coil is emitted inside the lamp body and need to be cooled by conduction to a heat sink at the lamp base, and also by radiation through the glass walls. The internal inductor lamps tend to have a shorter lifespan than the external inductor types due to the higher operating temperatures. They look more like a conventional light bulb than the external inductor-type lamps, more aesthetically pleasing in some applications.

For conventional fluorescent lamps, varying the composition of the phosphors coated onto the inside of the induction lamps allows for models with different colour temperatures. The most common colour temperatures of induction lamps are 3500, 4100, 5000 and 6500 K, but other colour temperatures and even coloured versions are available. The close regulation of the lamp's inductor by the ballast, and the use of microprocessor-controlled circuits, allows the electronic ballasts to operate at between 95 and 98 % efficiency. Only around 2–5 % of the energy is wasted in the induction lamp ballast compared to the 10–17 % wasted in traditional "core and coil"-type designs used with most high-intensity discharge (HID) commercial and industrial lighting.

Electrical conversion efficiency (sometimes stated as conversion efficiency) characterizes the capability of a lamp in converting electrical energy into light. The conversion efficiency is stated in Lumens per Watt (L/W) and is usually in a range since there is some "economy of scale" where higher wattage lamps tend to have higher conversion efficiencies than lower ones of the same type. The electrical conversion efficiency of the lighting depends on the technologies.

For example, the common incandescent lamps generally have a conversion efficiency of between 12.5 and 19 lumens per watt. Induction lamps have conversion efficiencies in the 68 to 87.5 Lumens/Watt range. This means you get more light output for the same amount of energy input or, stated another way, the same amount of light (when comparing lumen output) for less energy input. As another example, a 150 W metal halide lamp with a conversion efficiency of 65 Lumens/Watt (L/W) produces 9750 lumens. It could be replaced with a 120 W induction lamp with a conversion efficiency of 80 L/W and a light output of 9600 lumens saving 30 watts of energy for each lamp or fixture replaced.

There is a wide agreement and scientific data to show that the spectral distribution of the light produced by a particular lamp affects human vision. Higher blue output, sometimes referred to as "high scotopic output" lamps, appear brighter to the eye than the same wattage of lamp, with the same conversion efficiency, but with little or no blue output. Thus, the lamp's spectral output of light that is useful to the human eye is also a factor in perceived light quality and brightness. There is no scientific or industry-wide consensus for a terminology to describe this phenomenon as yet. The term visually effective lumens (VEL) is used here while others have used the term pupil lumens (PL). The VEL or PL of a lamp can be determined by multiplying the output in lumens by a conversion factor. The conversion factors are derived from the scotopic/photopic ratio (S/P ratio) of a lamp (see chart below). The S/P ratio measures the amount of light being output in the photopic sensitivity region, and the amount of light output in the scotopic sensitivity region, of the human eye, and then derives the ratio of the two. Photopic sensitivity, sensed by the cones, describes the ability of perceiving the colour. Scotopic sensitivity, sensed by the rods, describes the ability of perceiving the shades and greys.

When the ratio is used as a multiplier of the actual output lumens, the amount of light useful to the human eye (VEL or PL) can be determined. For example, a 100 Watt incandescent lamp with a conversion efficiency of 30 L/W provides 3000 Lumens of light—multiplied by its S/P ratio of 1.4, it is producing 4230 VEL—light useful to human vision. The S/P ratio correction factor drastically changes the conversion efficiency of the lamps.

The lamp type which had the highest conversion efficiency, low-pressure sodium (SO_X) at 100 ~ 180 L/W, is now one of the least efficient light sources at 35 ~ 63 L/W when corrected for S/P ratio. This is because the SO_X lamps produce nearly monochromatic yellow light. While they score high on the photopic curve (where conversion efficiencies are measured), they score low when corrected for VEL due to lack of blue output, which means a little light useful to human vision is produced by SO_X lamps.

The induction lamps have the highest energy conversion efficiency once the correction factor is applied (as they have a high S/P ratio of 1.96 or 2.25 depending on model). Induction lamps are therefore a better choice as they produce more light useful to the human eye (VEL) while consuming less electrical energy. Different light sources, based on the actual amount of light useful to human vision, which they produce, are compared.

Induction light, or electrodeless lamp, is a light source in which the power consumed to generate light is transferred from outside the lamp envelope to inside via electromagnetic fields. Compared with a typical electrical lamp that uses electrical connections through the lamp envelope to transfer power, there are three advantages of eliminating electrodes:

- Extended lamp life lying between 65,000–100,000 h depending on the lamp model, because the electrodes are usually the limiting factor in lamp life;
- The ability to use light-generating substances of higher efficiency that would react with metal electrodes in normal lamps; the energy conversion efficiency lies in the range of 62–90 lumens/watt (higher wattage lamps are more energy efficiency);
- Improved collection efficiency because the source can be made very small without shortening life, which is a problem in electroded lamps.

Apart from these three advantages, there are also the following advantages: because of the energy technology it uses.

- High power factor due to the low loss of high-frequency electronic ballasts which are typically between 95 and 98 % efficient;
- Minimal lumen depreciation (declining light output with age) compared to other lamp types as filament evaporation and depletion is absent;
- Instant on and hot restrike, unlike most conventional lamps used in commercial or industrial lighting applications (such as mercury-vapour lamp, sodium-vapour lamp and metal halide lamp);
- Environmentally friendly as induction lamps use less energy. It also uses less mercury per hour of operation than conventional lighting due to the long lifespan. The mercury is in a solid form and can be easily recovered when it is broken, or for recycling at end of life.

These benefits offer a considerable cost savings of between 35 and 55 % in energy and maintenance costs for induction lamps compared to other types of commercial and industrial lamps which they replace. There are also the following disadvantages that need to be noticed during the decision-making:

- Some models of internal inductor lamps that use high-frequency ballasts can produce radio frequency interference (RFI) which interferes with radio communications in the area. Newer, external inductor-type lamps use low-frequency ballasts that usually have FCC (or other certification); thus, they comply with RFI regulations.
- External inductor lamps tend to be quite large, especially in higher wattage models; thus, they are not always suitable for applications where a compact light source is required.

5.3 Lighting Design, Installation and Control

Well-designed lighting installations can provide very positive benefits to communities through reducing the perceived risk of crime, the enhancement of general public safety and generally adds to the feeling of well-being of a community through the positive message that well-maintained lit areas provide. The most effective way of reducing crime and fear by lighting is increasing the visibility and recognition over greater distance. The improved light lines deter potential offenders by increasing the perceived risks of offending. Pedestrians feel safer because they are less at risk of surprise attack and a pivotal cue to fear, darkness, is alleviated [18].

It is important to make sure that the overall performance of any lighting installation depends on both the equipment used and its correct installation. Any changes, substitutions or errors can have a profoundly negative impact on the resulting lighting installation performance. The designer will produce a scheme using specified luminaires with an oriented distribution, optical settings, lamps, mounting heights and aiming angles. Therefore, it is important that the installed luminaire complies precisely with the light output characteristics of the luminaire specified in the original design. Even superficially similar luminaires can have markedly different optical performances and in all situations the luminaire selected by the designer and approved by the local authority shall be used. Other parameters of the design such as the mounting height, the spacing between columns and tilt angle or position are equally critical in obtaining the design performance envisaged.

Energy consumption by lighting system is fundamentally determined by the lighting technologies, which have different conversion efficiency and light quality. For a particular type of lighting technology, the electrical power that is needed to meet the lighting requirement is the minimum demand. However, in reality, the lighting system usually consumes more electrical power than they actually need to meet the lighting requirement due to some uneconomical using behaviour. The behaviour is sourced from mainly three reasons: out-of-dated lighting knowledge, wrong judgement of lighting need and bad habit. Some light users have not been updated with the change of lighting knowledge, but are still with the “tips” spread in words of mouth a long time ago. For instance, there are still many people who think it is more energy saving to leave the lighting on rather than turn it off, because they believe the fact that it consumes ten times more of electrical power to start the lighting up than to keep it on. Despite the awareness of consuming lighting in an energy-saving way, oppositely these lighting users, who are not updated with the recent lighting knowledge, waste a considerable amount of electricity during the daily use of lighting. The second behaviour, wrong judgement of lighting need, happens due to incorrect evaluations of lighting need by the users. Taking offices as an example, during daytime, the office lightings are turned on even when there is plenty of daylight in the office or when they work on the computer most of the time. This leads to an extra approximately 10 % consumption of electrical power for an office building [19]. The third one is the bad habit of using lighting. Usually, an open plan office is shared by many people. Very often, the lighting is left on all night even when there is nobody working in the office. The habit of turning the lighting off when it is not needed has not been adopted by everybody.

To mitigate the unnecessary energy consumption caused by the lighting users, the control solutions are essential and must be adopted to permit the optimal way of utilizing the lighting system, avoiding the unnecessary consumption of electricity caused by the users. Building automation and lighting control solutions, which can achieve considerable amount of energy savings [20–23], are now available to help reduce energy usage and cost by eliminating over-illumination. These solutions provide centralized/networked control of all lighting within a home or commercial building, allowing easy implementation of scheduling, occupancy control, daylight harvesting, individual customization and dynamic variation for the users at different tasks or with different lighting preferences [24, 25]. The importance has been found in relationship between lighting satisfaction and an office worker's mood and productivity [26].

Many newer control systems are using wireless mesh open standards (such as ZigBee), which provide benefits including easier installation (no need to run control wires) and interoperability with other standards-based building control systems. In responses to daylighting technology, daylight-linked automated response systems have been developed to further reduce energy consumption. These technologies are helpful, but they do have their downside. Very often, rapid and frequent switching of the lights on and off can occur, particularly during unstable weather conditions or when daylight levels are changing around the switching illuminance. Not only does this disturb occupants, it can also reduce lamp life. A variation of this technology is the "differential switching or dead-band" photoelectric control which has multiple illuminance it switches from so as not to disturb occupants as much.

5.4 Life Cycle Assessment

Life cycle assessment analyses the entire life cycle of the products or services with regard to the environmental impact and to display these analyses in a transparent way. It is grounded on the same basic principle with varying areas of application extending from carbon footprints, water balances, analyses of material flows and processes to examinations of social and economic factors. By considering the whole life cycle of a product or service, incurred environmental impacts, not only be partially avoided, but the exposed for analysis. This allows us to determine in which phase of life, either the production of raw materials or the disposal, causes the greatest harm to the environment. The life cycle assessment includes the energy consumption, the water usage and the produced waste.

As shown in Fig. 5.1, in the whole life cycle of a lamp, resource, energy and water need to be consumed to source and refine the raw materials, manufacture the products and transport the products for distribution and sale. When the lamp comes to the end of life, the lamp produces waste. In its servicing period, energy

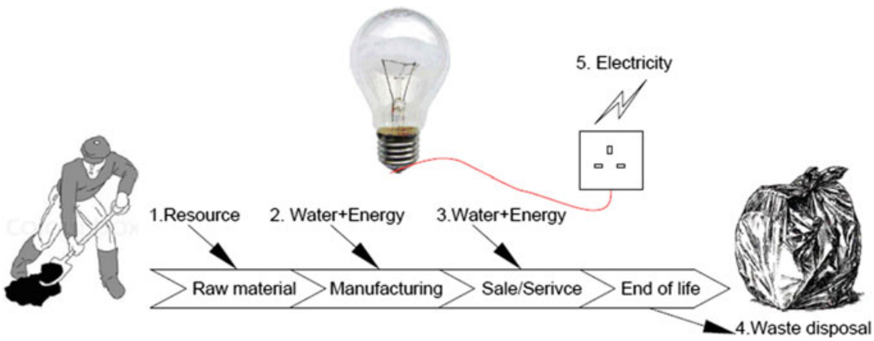

Fig. 5.1 Life cycle of a lamp

consumption occurs during its use and the maintenance. In order to let the lamp go green, it should reduce water usage, energy consumption in the whole life cycle and reuse/recycle the lamp when it comes to the end of life.

The ideal life cycle should be a closed-loop cycle, as shown in Fig. 5.2, where the sustainability is fulfilled by maximally reducing the energy and water usage and totally reusing the components when the lamp comes to the end of life. Obviously, the lamp is manufactured to meet our need for lighting by converting the electricity into light. The use in its life period not only has impact to our need by providing light, but also to our environment by consuming electrical energy. Figure 5.3 shows the actual life cycle of a lamp because in real circumstance, for most of the

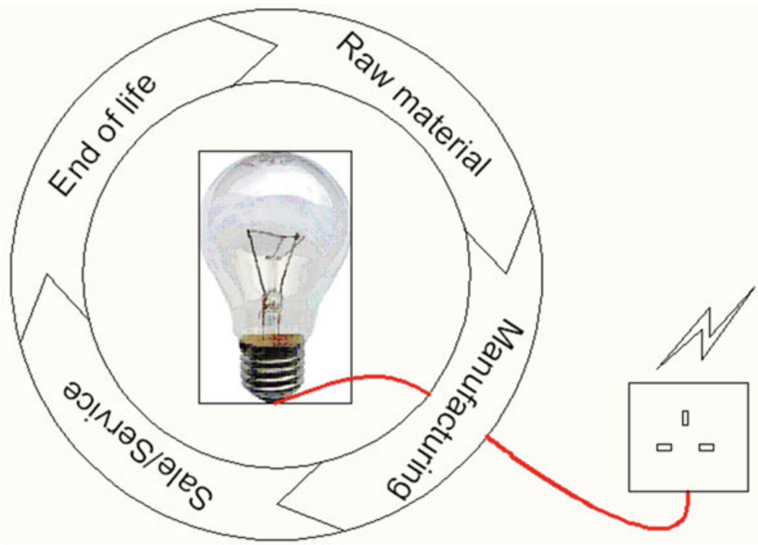

Fig. 5.2 Ideal life cycle of a lamp

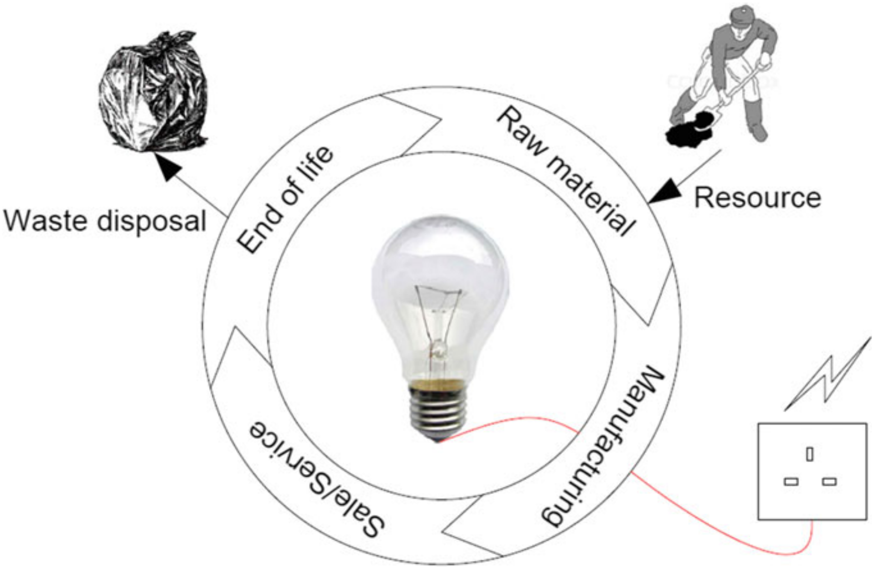

Fig. 5.3 Actual life cycle of a lamp

products, it is difficult to totally recycle or reuse every part of the products which come to the end of life. There are still some parts which have to be disposed. The mission is to minimize the waste disposal to the environment and the need of new materials. This can be achieved by maximally reusing, recycling and reconstructing on the basis of achieving a positive economic and environmental impact.

The overall characteristic of a given lamp is going to be discussed according to these elements in the circle.

5.4.1 Sources of Raw Materials

Sustainably sourcing the raw materials for the products is the beginning of establishing the sustainability of the products. The raw material sourcing should be based on the minimum impact to the environment. It should avoid excessive use or exploration of the local environment or resources by correct raw material recovery assessment and strict monitoring regulation. It should be based on the sustainable standard to eliminate/reduce the negative environmental impact. The establishment of an environmentally friendly sourcing for the raw materials adds the sustainable value to the product which in turn creates the credit in the product.

Therefore, in the procurement, attention must be paid to the sustainable value of the products. Measures must be taken to engage with the suppliers and contractors to ensure that goods and services are sustainably procured and meet the company's environmental regulations. Incentives are necessary to be given to the manufacturers to improve their own sustainable environmental performance. Suppliers should be encouraged to achieve environmental credentials (ISO 14001 or EMAS).

5.4.2 *Manufacturing*

The water footprint is an indicator of water use of a consumer or producer. The water footprint of an individual, community or business is defined as the total volume of freshwater that is used to produce the goods and services consumed by the individual or community or produced by the business.

The increasing consumption of water and overuse of aquatic systems has already resulted in a dramatic deterioration of aquatic ecosystems worldwide. This disruption has lead to a shortage of freshwater availability in some regions of the world. The consequences of overuse will be multilayered ranging from supply dropouts to significantly higher prices for potable water. This means companies need to especially manage their water footprint—the risk of high direct water consumption at their own sites and indirect water consumption in their supply chains.

Gas emissions that contribute to the global warming effect are measured as the product carbon footprint (PCF). During a product's life cycle, energy is required to extract, transport and refine raw materials; to manufacture and distribute the final product; and treat the waste at the end of its useful life. As fossil energy carriers currently play the main role in supplying energy, all of the above listed steps are associated with the generation and release of greenhouse gases (GHG) such as carbon dioxide, methane, nitrous oxide, etc. These gas emissions in turn contribute to the global warming effect, which is measured as the product carbon footprint (PCF).

5.4.3 *Logistics, Sale and Services*

Logistics is the integrated management of all the activities required to move products through the supply chain. For a typical product, the supply chain extends from a raw material source through the production and distribution system to the point of consumption and the associated reverse logistics. The activities mainly consist of freight transport, storage, inventory management, materials handling and all the other related processing. When the products come out from the factory, they are distributed to different regions for sale. This involves transportation and sale in marketing place, followed by the installation and maintenance service. These procedures consume water and energy, which is represented by No. 3 in Fig. 5.1.

5.4.4 End of Life

When the products come to the end of life, the disposal of the products would be an important issue that needs to be managed considering the environmental impact. Will they go back to the environment directly in processes like land filling or combusting or will they be reused by the manufacturer? This determines the sustainability of these products that are used to serve our society. This assessment adds extra green value to the products if the products can be recycled by the manufacturer. A monitoring regimes need to be established to trace life cycle of the products, from raw material sourcing to disposal plan when it comes to the end of life.

For the lighting products, the treatment of the old lightings which are replaced by the upgraded lamps need to be considered. It is best to be reused or recycled which can be realized either by the lighting company or the company which is specialized in recycling the lamps and components. This can add extra value of sustainability to the products by reducing/eliminating the waste and impact to the environment.

The production process of white LEDs is complex, and many aspects have room for further improvements. This means that the production price is still relatively high compared to traditional light sources. The process used to deposit the active semiconductor layers of the LED is constantly improved to increase the yields and production throughput. The phosphors, which are needed for their ability to emit a broader wavelength spectrum of light, problems tuning the absorption and emission and inflexibility of form, have been issued.

CO_2 emission: Both LED and induction lamps offer a reduction in CO_2 emission from power generation. The exact amount depends on the mix of fossil fuels used for power generation in the area where the fixtures are operating, and the total amount of energy saved. Induction lighting offers more significant energy savings than LEDs, thus offering greater CO_2 reductions. In an increasing number of jurisdictions, organizations which reduce power consumption and the related CO_2 emission are eligible for "carbon credits". It can be used to offset other sectors within the organization that are not as efficient, or can be traded or sold.

Toxic substances: As with the manufacturing of any semiconductors, toxic chemicals are used in the fabrication of LEDs. Those of most concern are lead and arsenic as both are used in the process. However, the amounts present in finished LEDs are minute, usually fully encapsulated and should not cause any local contamination. Induction lamps contain mercury which is a toxic, persistent, bio-accumulative substance. Almost all modern lighting sources depend on using mercury inside the lamps for operation. When considering the environmental impact of the mercury in lighting, we must take into consideration: [1] the type of mercury (solid or liquid) which is present in the lamps, [2] the amount of mercury present in a particular type of lamp and [3] the lifespan of the lamp which will determine the amount of mercury used during operation.

Liquid mercury, which is the most common form of mercury used in HID and fluorescent lighting, represents the greatest environmental hazard. Mercury can be compounded with other metals, into a solid form called an amalgam which is the type of mercury used in magnetic induction lamps. It is similar to the once widely used amalgam in dental fillings, the solid form of mercury (amalgam) poses much less of an environmental problem than liquid mercury. Induction lamps use the least amount of mercury of any lamp technology, when considered based on both initial quantity, and amount used over the lamp's life. Magnetic induction lamps are more environmentally friendly since they use very little mercury over their lifespan. Further, the mercury is in solid amalgam form, reducing contamination in the case of breakage. The chart below shows the amount of mercury used in induction lamps and other lighting technologies based on consumption per 20,000 h of operation.

Recycling: One should also consider the environmental impact of the lighting once it has reached the end of life. There is little available information about the recycling of LEDs. Since the LED contains plastic and metals, theoretically the metal components could be recovered and recycled. In the case of induction lamps, the solid mercury amalgam can be recovered and recycled. Once the inductors are removed, the lamp body can be recycled as it is made of glass, while the inductors themselves can be recycled into their metal components [27].

5.5 Conclusion

Reducing our environmental impact and carbon footprint are worthy goals which can make a difference in climate change. Lighting consumes a significant fraction of energy production with its attendant CO_2 emissions. By installing energy efficient lighting systems, we cannot only reduce energy costs and expenditures, but also reduce environmental impact through reduced CO_2 emissions from electricity generation, reduced waste and improved recycling. When comparing various lighting technologies used in industrial, manufacturing and retail applications, it becomes clear that induction lamp-based lighting fixtures offer the best environmental characteristics when compared to the most commonly used lighting technologies.

When compared to the two most commonly used lighting technologies in commercial and industrial applications (metal halide and high-pressure sodium lamps), induction lamps offer the following benefits:

- Significant reduction of electrical energy consumption;
- More light output when corrected for VEL/PL;
- Significant reduction in CO_2 emissions from electrical power generation due to reduced energy consumption;
- Secondary energy consumption reduction through reduced thermal loads thereby saving HVAC costs and energy, and the ability to use on-demand technologies such as occupancy sensors due to the "instant on" feature of induction lamps;
- Extended lifespan which reduces the materials needed for replacement lamps compared to MH, HPS and SO_X lighting technology;

- Low mercury consumption over the induction lamp lifespan compared to competing lighting technologies;
- Induction lamps use a solid mercury amalgam which produces significantly less environmental contamination than other technologies, if accidentally broken. The sold mercury amalgam is also easy to recover and recycle at end of lamp life;
- End of life deconstruction for recycling and materials recovery requires less energy.

Magnetic induction lamps represent not only a breakthrough in energy efficient lighting, but also a sound environmental choice, when all aspects of the lamp technology are considered. However, the induction lamps are currently limited in the commercial and industrial application due to large lumen output.

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Chapter 6
Applications of Air-to-Air Energy Recovery in Various Climatic Conditions: Towards Reducing Energy Consumption in Buildings

Mardiana Idayu Ahmad, Fatin Zafirah Mansur and Saffa Riffat

Abstract A substantial increase in world energy consumption has resulted in global rising pattern of building energy consumption. This trend is predicted to continuously rise as a result of economic prosperity and accelerated growth in living standards for shifting to contemporary lifestyle. Hence, the need for energy-efficient technologies in buildings is pivotal in order to reduce energy consumption and mitigate global environmental impact. Amongst these technologies, the application of air-to-air energy recovery system is proven as one of the significant solutions towards reducing energy consumption and providing fresh outdoor air in buildings. The system is defined as a mechanical system that able to conserve energy by transferring heat or mass from a stream at a high temperature to a low-temperature stream through a core. It was also able to remove stale, polluted air indoor spaces and replaces it with fresh outdoor air. In order to have an in-depth understanding of the system, this chapter discusses the mechanism and the application of the system in various climatic conditions such as winter and summer conditions; cold and extremely cold climate conditions; and hot–humid condition.

Keywords Air-to-air energy recovery · Building applications · Mechanism · Climatic conditions

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6.1 Introduction

In modern times, most people spend about 90 % of their times indoors; thus, the physical conditions of the indoor spaces would directly influence the life quality health and productivity of the occupants. By looking at these factors, the need in providing comfortable indoor environment and having a decent standard of living for the occupants is absolutely necessary. In addition, majority of people today believe that preventing the outdoor air from entering buildings would allow them to maintain cleaner and healthier indoor air. However, according to the US Environmental Protection Agency [1], indoor air is two to five times more polluted as compared to outdoor air. Indoor air contains a large number of different harmful pollutants, and thus, the high accumulation of these pollutants can cause health and comfort issues for occupants, leading to sick building syndrome (SBS) [2–4]. In order to overcome this, hence, consideration should be given in providing adequate ventilation to ensure good indoor environmental quality is achieved in indoor spaces without compromising occupants' comfortable level. One of the efficient solutions to meet this demand is by the utilisation of heating, ventilation and air-conditioning (HVAC) systems or normally known as air-conditioning and mechanical ventilation (ACMV) systems in hot–humid regions. Nonetheless, the use of these systems require a large amount of energy depending on efficiency of the system components, climatic conditions and whether the systems are appropriately sized for their host indoor spaces.

Energy consumption for HVAC or ACMV systems used by building sector accounts approximately 50–60 % of the total final energy demand [5, 6]. It has been reported that HVAC system in the USA accounts approximately 20 % out of 50 % of total energy consumption in buildings [7] and about 57 % in the EU [8]. In addition, as reported in Energy Outlook for Asia and the Pacific, the major usage of electricity is contributed by HVAC or ACMV systems in either residential or commercial buildings [9]. On the other hand, in Southeast Asia, building sector has consumed about 30 % of total final consumption [10], which mostly contributed by HVAC systems in terms of air-conditioning equipment. Findings by Kubota et al. [11] showed that the average energy consumption on air-conditioning equipment is 1.4 larger than without air-conditioning unit in hot–humid climate region. Well-insulated and tight buildings also have resulted in the energy demand for heating from ventilation air, which tends to reach about 60 % of the total annual energy demand [12]. These percentages are predicted to increase due to the rapid growth of energy consumption in line with the rising living standards and urbanisation support for shifting to modern lifestyle. Hence, the need for energy-efficient technologies with less utilisation of natural resources would be an ideal choice to reduce energy consumption and mitigate environmental impact.

In order to create an idea of environmentally friendly building aside from the standard energy conservation approach, innovative technologies must be implemented in the building, which suggested the installation of air-to-air energy recovery system [8, 13]. The system is scientifically proven as one of energy-efficient technologies that aids in improving indoor environmental quality and reducing energy consumption, thus encourages the approach of developing green and sustainable buildings. Moreover, the system helps in reducing the air-conditioning demand especially for the tight buildings by reducing the contribution of total outside air to the air-condition load [14, 15]. The system was also able to reduce about one-third of annual cooling and heating energy consumption [15]. A substantial amount of energy is recovered by using the system to precondition the ambient fresh air, which in return reduces the overall HVAC or ACMV energy requirement [16]. With the aim to have a deeper understanding about the air-to-air energy recovery system, this chapter discusses the mechanism and the application of the system in various climatic conditions such as winter and summer conditions; cold and extremely cold climatic conditions; and hot–humid condition.

6.2 Mechanism and the Use of Air-to-Air Energy Recovery System Towards Reducing Energy Consumption in Buildings

Air-to-air energy recovery system is defined as a device that is able to remove in terms of extract, recover or salvage heat or mass from one airstream and transfer it to another airstream using mechanical approach. This means that the energy that would otherwise be lost is utilised to pretreat the incoming air, helping to maintain a comfortable temperature of an indoor space. Thus, this system aids in preheating the incoming air during winter or cold condition and precooling the incoming air during summer or hot condition and eventually reduces annual operating costs by reducing the required heating and cooling capacity [17]. In general, there are two main classifications of air-to-air energy recovery system: (i) sensible air-to-air energy recovery system and (ii) total air-to-air energy recovery system. Thorough reviews on this technology are reported in [13] and [18]. Based on the reviews, a lot of works have been conducted with regard to numerical, simulation and experimental approaches of the system. However, a gap still exists between research results and practical applications, and therefore, future investigation should be established concerning these areas to better evaluate the feasibility and reliability of the system in building services.

Recently, researchers, designers and engineers have focused and explored on the development of the system to be integrated with HVAC systems gearing towards commercialisation by means of new design approaches and mechanisms [19–26]. Besides, in assisting testing, rating and utilisation of the system, several documents have been published by HVAC industry. These include American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 84–1991 and Air-Conditioning, Heating, and Refrigeration Institute (AHRI) Standards 1060. ASHRAE Standard 84 is American National Standards Institute (ANSI) standards that aim to determine the Method of Testing Air-to-Air Heat/Energy

Exchanger by highlighting: (i) uniform method for testing to obtain performance data; (ii) calculation method and report procedures for performance testing; and (iii) specific types of test equipment for performance test. It also provides techniques in minimising air leakage. On the other hand, AHRI Standards 1060 highlight the Performance Rating of Air-to-Air Exchanger for Energy Recovery Ventilation which envisions the definitions, test requirement, rating requirement and minimum data requirement, mainly for rating, marking and conformance conditions intended by the industry. Thus, this standard is subjected to a factory-made air-to-air energy recovery device. AHRI 1060 has also established a Certification Programme 1060 to verify ratings provided by manufacturers. In general, air-to-air energy recovery for commercialisation usage must be tested in accordance with ASHRAE Standard 84, except where modified by AHRI Standard 1060.

This system can reduce electricity and gas consumption in HVAC system, allowing a smaller air-conditioning system to be installed and providing better indoor air quality [27]. The implementation of the system is believed to save a large fraction of thermal load and improve the existing HVAC system that is very energy-intensive to remove both sensible and latent loads [14]. Besides, it is also claimed to provide a low operating cost, which aids in reducing ventilation load of an air-conditioning system [28]. In addition, adaptation of the system in commercial laboratories discovered that the system could substantially reduce the mechanical heating and cooling requirements related to ventilation in the laboratories [29]. When the system is applied in summer or hot condition, less moisture air is brought into indoor space, which subsequently has led to less work for the air-conditioning system [30, 31].

It was reported by Mohammad et al. [32] in their works that 20–35 % of potential energy savings for annual energy consumption was achieved by employing air-to-air energy recovery based on climatic conditions. This study was conducted based on TRNSYS simulations for a ten-storey office building in four locations in North American, representing major different climatic conditions. It was found that the savings in hot-humid were more significant than the other climatic conditions as the moisture transfer in the system able to reduce the dehumidification load. In addition, the system was studied in a cold climate region of Greece by Papakostas and Kiosis [33] with the aim to capture energy reduction of a heating system. It was found that 43 % reduction in boiler gas consumption and 16 % reduction in chiller capacity result to an annual energy saving of approximately 40 %. Based on these data, thus, future works should be carried out to investigate the impact of various climatic conditions such as cold climate, hot and humid climate, hot and dry climate and feasibility in terms of performance of the system using experimental and field-testing approaches. On the other hand, a work by Delfani et al. [30] showed about 11–32 % of total energy consumption for building air conditioning in hot–humid conditions was achieved by using air-to-air energy recovery system combined with cooling coil. Investigation of air-to-air energy recovery system was also conducted by Zhang and Zhang [34], and they reported that the system could save over 60 % of energy for air-conditioning operating hours by testing the system under various outdoor conditions based on experimental data set in laboratory. Experimental investigation of an air-to-air energy recovery system with an air-side economiser was also carried out in both cold and hot climates and revealed greatest energy benefits gained [35].

6.3 Application in Winter and Summer Conditions

Application of air-to-air energy recovery system in winter and summer conditions is aimed to provide energy savings in heating and cooling systems. It provides savings in summer cooling and winter heating operations and thus is able to decrease the energy peak load demand. In addition, the system was able to improve humidity control during both conditions. There a lot of studies can be found in the open literature with regard to investigation of this system in winter and summer conditions [13]. Amongst these studies, a quite recent performance investigation of air-to-air energy system was carried out in China, which focused on sensible heat efficiency during winter [36]. It was found that the energy percentage was saved at a large amount of 16.2 % with an efficiency of 75 %. On the other hand, Zhou et al. [37] carried out a simulation study using EnergyPlus to investigate the feasibility of an air-to-air energy recovery system during winter condition in Shanghai and Beijing, China, and found that the feasibility of the system in Shanghai was better. Another study on the potential application of air-to-air energy recovery in a supermarket during winter in China was conducted by Kang et al. [38] throughout the coldest month. The cities involved were Harbin, Beijing, Shanghai and Guangzhou. It was found that due to the internal moisture emissions that were already high, latent heat was not suitable to be used for ventilation energy savings in the region. In this case, future studies should be carried out to further improve the system by taking into account moisture emissions. Considering the findings in [38], Zhang et al. [39] performed a similar study and concluded in their study that latent heat was less important as compared to sensible heat in cold areas.

Another study was carried out using TRNSYS in Mediterranean region in both cold and hot seasons and indicated that the system was more effective in winter than in summer [40]. An investigation on air-to-air energy recovery system in a real existing building during humid summer condition was conducted in Ottawa and it was found that the system was capable of reducing air-conditioning electricity consumption which was up to 20 % [31]. Besides, Fan and Ito [41] modelled the impacts of inlet and outlet opening arrangements through an air-to-air energy recovery system on energy consumption in typical office space equipped with air-conditioning unit during summer condition in Japan by using the approaches of building energy simulation (BES) alone and integrated BES–computational fluid dynamic (CFD) analyses. Field measurements were also carried out to validate the simulation data. The results indicated that significant differences were achieved in both approaches. More studies in relation to air-to-air energy recovery system using building simulation approaches should be carried out in the future in other climatic conditions.

6.4 Application in Cold and Extremely Cold Climatic Conditions

Scientific evidence has proven that air-to-air energy recovery system is a reliable system for energy savings in winter and summer conditions and is used for ventilation purposes throughout the world. Through a study of life cycle assessment (LCA) of residential ventilation units in cold climate, it was reported that by adopting the air-to-air energy recovery system, a net positive impact towards the environment can be achieved. However, the system is a relatively new technology in extremely cold climate as the early models of air-to-air energy recovery system experienced frosting in below-freezing temperatures [42]. Later, with the advancement in technology, new models with modification for defrosting were introduced, with a specification to be used in cold and extremely cold climatic conditions [43]. The earliest studies of air-to-air energy recovery system for cold and extremely cold climatic conditions with defrosting modification were carried out by Kragh et al. [44] and Nielsen et al. [45]. From the studies, it was found that the system had the ability to continuously defrost itself at air temperature below freezing point with some modification on the flow arrangement without using any supplementary heating. The efficiency of the system was recorded about 85 % at dry condition. Meanwhile, at freezing condition, the system efficiency was achieved at 88 %.

Garber-slaght et al. [46] observed that the performance of several commercial air-to-air energy recovery systems in cold climate did not suffer any of the mechanical failure from frost accumulation due to implementation of sufficient defrost mechanism. In the study, it was reported that the system gave significant results on the efficiency and also had specific time in defrost mode. It was also explained that adaptation of the system in cold climate was mainly to aid in maintaining the interior humidity levels of dry and arid conditions during winter. An investigation on air-to-air energy recovery system focusing on apartment buildings in cold climate was carried out by Alonso et al. [47]. They compared the sensible heat exchanger with membrane-based heat exchanger and found out that the membrane-based heat exchanger with runaround energy recovery was more promising in cold climates. In addition, Alonso et al. [48] studied a prototype of an energy exchanger by comparing plastic type and membrane-based in cold climate condition. It was identified that the system adopted in cold climate with membrane-based-type energy recovery showed a little freezing and condensation problem than the plastic type. Besides, a comparison investigation between a plastic type and membrane-based type air-to-air energy recovery system found that the membrane-based type materials were expanded and crumpled in humid condition, and as the humidity was low, it was tighten back as usual and presented better efficiency than plastic type that showed a formation of ice and condensation [49]. From these studies, it can be seen that the application of air-to-air energy recovery system is feasible in cold and extremely cold condition; however, some of the systems may face condensation problem. Thus, studies on modification or enhancement of the flow arrangement and materials of heat and mass transfer surface of the system should be established in the future to mitigate this problem.

6.5 Application in Hot–Humid Condition

Air-to-air energy recovery system was introduced in hot–humid condition to assist ACMV systems in maintaining good indoor air quality and thermal comfort in indoor spaces. The system was able to transfer both sensible and latent heat from the incoming fresh air to the outgoing air, thus aids in reducing the load (the ventilation) on the air-conditioning system [31]. A comparison study was performed between air-conditioning system coupled with an air-to-air energy recovery and a conventional air-conditioning system based on energy analysis and resulted in up to 8 % annual energy consumption saving in tropical climate that was found for the system with air-to-air energy recovery system [16]. This denoted that the system has significant contribution towards energy saving by reducing the latent load in hot–humid condition. Al-Waked et al. [50] studied three models of membrane-based air-to-air energy recovery system for building applications in hot–humid conditions using CFD simulation and found that the system could resist moisture transportation. Feasibility study of an integrated heat and air-to-air energy recovery system with a built economiser was evaluated quantitatively using an excel-based analysis tool and discovered that the system provided high energy saving and was significant to be used in hot–humid condition [39]. Even though a few studies have been conducted on the performance of air-to-air energy recovery system for hot–humid condition, studies based on experimental approach, performance-based weather data and simulation are very limited in the open literature. Besides, investigations on physical components of air-to-air energy recovery such as heat exchanger materials, fans and ducting system for both sensible and latent recovery applications in hot–humid conditions should be further explored.

6.6 Conclusion

Air-to-air energy recovery system is a mechanical system that able to remove stale indoor air for an equal amount of fresher outdoor air. This system is scientifically proven as one of energy-efficient technologies which can be applied in buildings in different climatic conditions. In winter or cold condition, it retains heat and moisture from exchanged air; meanwhile, in summer and hot–humid conditions, it preconditions and dehumidifies the incoming air. Numerous studies have been carried out pertaining to this technology which vary from fundamental to applied investigations. However, studies based on experimental approach on the performance and practical investigation in real existing buildings of this system in various climatic conditions are quite limited especially in hot–humid conditions. In addition, economic, environmental and energy analyses about this system should also be considered in the future.

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Chapter 7
Toplighting Systems for Improving Indoor Environment: A Review

Karam M. Al-Obaidi and Abdul Malek Abdul Rahman

Abstract Toplighting systems represent an optimum source of natural light for building interiors. These systems provide abundant illuminance levels from small openings, thus reducing artificial lighting and minimising glazing areas. However, based on a geographic location, these systems transfer high sunlight levels, which directly affect the performance of indoor environment. Therefore, studying their potentials requires proper understanding. The aim of this research is to emphasise the critical design concepts in different places and provide an indication of the characteristics of these global system designs. The method of this study is theoretically based on descriptive analysis to assess design requirements. This study includes a discussion on different methods and standards, which deeply and systematically deliberated several trends such as comparative benefits and limitations. This chapter presents a holistic view of selecting toplighting systems during the design stage, which makes the review a useful source for architects, building designers, and practitioners.

Keywords Toplighting systems · Daylighting · Design strategies · Passive architecture

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7.1 Introduction

Passive architecture involves designing a building to reduce the need for mechanical controls of heat, light, and sound to a minimum, as well as to take advantage of climatic elements to maintain human comfort. Sunlight and daylight represent the core of this passive approach as they are freely delivered daily in high or low quantity [1]. Since the early twentieth century, daylight is the main light source in buildings. In the 1950s, electrical lighting had transformed the life of indoor environment by providing most or all user lighting necessities.

Electrical light sources include different types, such as incandescent, energy-efficient fluorescent lamp, cool-white fluorescent lamp, and full-spectrum fluorescent lighting, wherein every sort has various energy consumption level and different spectra. However, these sources have insufficient blue colour content in their light spectrum [2]. Blue spectrum, which is greatly delivered by daylight, is good for human beings. Edwards and Torcellini [3] showed that majority of electrical light sources, even though they are full-spectrum fluorescent lighting, have insufficient spectral distribution to supplement biological functions.

Occupants feel more comfortable with variable light in the form of daylight as it provides connection to the natural environment. Natural light ensures a balanced colour spectrum as its light energy peaks are slightly in the blue-green portion of the visible spectrum [2]. Furthermore, daylighting has been related to reduced eyestrain and headaches, lower fatigue, seasonal affective disorder, and improved mood. Joseph [4] indicated that people in full-spectrum daylight spaces reported an increase in satisfaction and improvement in health and healing process.

Therefore, concerns about environment and energy have led to a rethinking of lighting design [3]. Many studies and recent technological developments decisively show that daylight system, especially toplighting, can save electrical consumption in many applications. According to the US Department of Energy, savings from daylighting can reduce lighting energy use in some buildings by up to 80 %. Studies in the Southeast Asian region indicated that using daylight systems in buildings can cut down the total energy demand by 20 % [5]. This strategy possesses a good potential for application especially in tropical buildings due to a year-round plentiful sunshine [6, 7].

Given that daylight strategy is a renewable energy that will considerably improve the indoor environment within any building, using toplighting systems can deliver considerably more suitable illumination from small openings than side-lighting systems. Rooflight systems provide three times more light than the same area of vertical glazing [8, 9]. However, their exposure to sunlight is approximately 10 times brighter than light from the sky for normal openings.

The aim of the research is to emphasise the critical design concepts in different places and provide an indication of the characteristics of these global system designs. Only the issues on daylight in passive and sustainable architecture will be covered, and materials related to the technological field are not covered.

7.2 Toplighting Types

Windows are apertures in a building envelop that allow light and air into indoor spaces; these indoor spaces can be divided into two major categories: first, the openings located in the sidewalls of a building and second, the apertures from the roof commonly known as rooflights [10]. The general terms used by building specialists for these two classifications are side-lighting and toplighting, respectively.

Given that this study focuses on toplighting systems, identifying their potentials is required. Toplighting can give the designer the opportunity to have a better choice of source placement to provide more uniform illumination from the sky and to improve privacy and security [11]. The main limitations for these systems are the structural design, electrical system, mechanical system, fire safety equipment, as well as their implantation in tall buildings due to their ability to illuminate only the upper floors [11].

In Lighting Guide LG10 publication (1999) titled 'Daylighting and Window Design', a number of rooflight categories are indicated. The publication revealed that shed roof, monitor, and sawtooth are the most common toplighting systems (Fig. 7.1).

Toplighting systems can also have horizontal, vertical, tilted, or domed glazing according to Phillips [1], the European Commission Directorate-General for Energy [10], Kroelinger [11], and Ruck and Aschehoug [12]. Toplighting systems are classified as:

(a) **Skylights (rooflight)**

They comprise a light-transmitting fenestration placed horizontally on flat or sloped roofs, forming all or a part of the roof structure with the potential to deliver a uniform level of illumination over an interior space. It is an effective approach for illuminating one-storey buildings. However, its performance varies under overcast and clear skies, especially under the concern of thermal impact in hot regions.

(b) **Roof monitors or clerestory**

They are raised or elevated roof planes. Their glazing may be vertical or sloped. They illuminate task areas under each monitor bay. However, their utilisation requires specific orientation as monitors should face east and west directions.

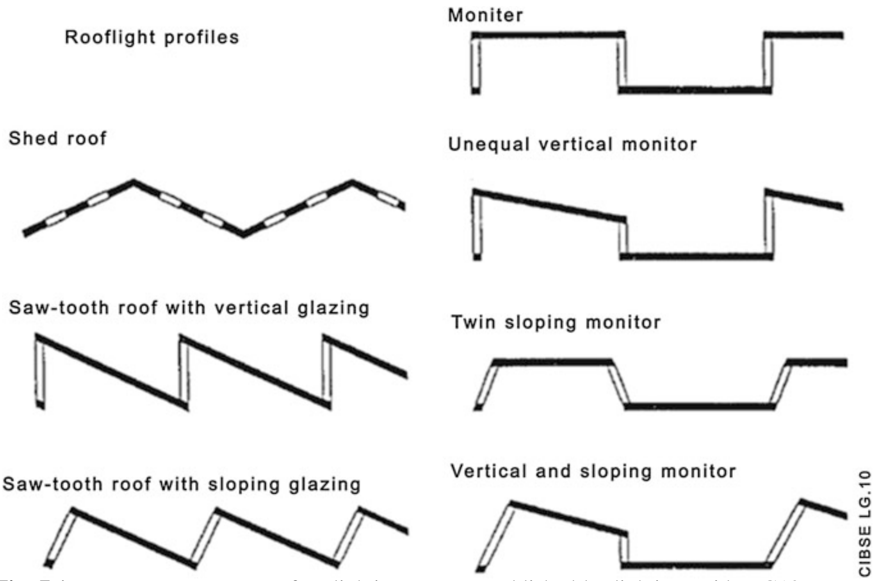

Fig. 7.1 Most common types of toplighting systems published by lighting guide LG10

South-facing monitors perform differently from north-facing monitors. They are commonly found in tall buildings and usually associated with other types of aperture at low levels to offer the main daylight.

(c) **Sawtooths**

They are openings with an angled slope of 45° or vertical glazing fitted on a sloped roof plane. They are effective when installed in series of three to avoid the equator direction and thus capture more diffused light. The opaque portion of angled glass should preferably be covered with a well-insulated cool roof and radiant barrier.

(d) **Courtyard and lightwells**

Courtyards are external spaces open to the sky in the ceiling that permit daylight penetration to the floor and are moderately or completely bounded by the building. The potential of courtyards increases in the northern orientation to decrease glare and minimise the need for sun control. Treatment of building fabric and floor finishing to reflect sunlight and daylight without increasing the level of glare for occupants must be considered. Meanwhile, lightwells are functional shafts for daylight that provide ventilation. They comprise an unoccupied space but function more as a source of supplementary light. Their performance relies on the aspect ratio and depth of the shaft.

(e) **Atria**

It covers a large portion and is normally central to a building design. A modern atrium can be glazed to provide a proper indoor environment whilst allowing for ventilation and reducing the need for air conditioning. Short and wide atria create better conditions than tall and narrow atria. The performance of daylight in an atrium design is complex. It relies on the aspect ratio, orientation, geometry, feature of the floor and wall surfaces, and nature of the glazing roof materials.

(f) **Light tubes and light ducts**

They are considered mechanically complex daylighting devices. They were invented by Solar Tube International in 1993. Their mechanism depends on sunlight to collect light through mirrors controlled by a tracking device, concentrated by means of lenses or mirrors, and then directed inside the building through acrylic rods or fibre-optic cables for light tubes or shafts and light ducts. The tube itself is a passive element that comprises either a light-directing fibre-optic bundle or a simple reflective interior coating. In fact, their potential depends on direct sunlight. They are considered cost-effective only in regions where clean air and blue skies can be assured throughout the year.

A study conducted by the Collaborative for High Performance Schools [13] demonstrated the performance of the most common types of toplighting systems; such performance is shown in Fig. 7.2.

Design Criteria	View Windows	High Sidelight w/ Light Shelf	Wall Wash Toplighting	Central & Patterned Toplighting	Linear Toplighting	Tubular Skylights
Uniform Light Distribution	○○	●/○	●	●●	**O**	**O**
Low Glare	○	●	●	●	●	●/○
Reduced Energy Costs	○	●	●	●●	●	●
Cost Effectiveness	●	●	●	●	●	●●
Safety/Security Concerns	○	●/○	●	●	●	●●
Low Maintenance	○	●	●	●	●	●

●● Extremely good application ● Good application ○ Poor application ○○ Extremely poor application **O** Depends on space layout and number and distribution of daylight apertures ●/○ Mixed benefits

Fig. 7.2 Performance of the most common types of toplighting systems [13]

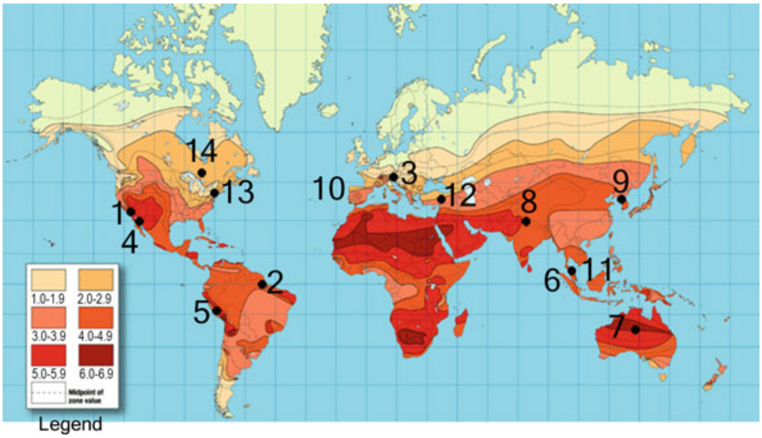

Fig. 7.3 Location of surveys implemented according to the *World Insolation Map* (*sun hour equals 1 kWh per square metre per day*) (*1*) Lee et al. [14]; (*2*) Cabús and Pereira [15]; (*3*) Kristl and Krainer [16]; (*4*) McHugh et al. [17]; (*5*) Beltran [18]; (*6*) Ibrahim et al. [19]; (*7*) Darula et al. [20]; (*8*) Chel et al. [21]; (*9*) Kim and Chung [22]; (*10*) Yunus et al. [23]; (*11*) Acosta et al. [24]; (*12*) Yildirim et al. [25]; (*13*) Ghobad et al. [26]; (*14*) Laouadi et al. [27]

To understand the performance of these systems effectively, next part summarises several studies on different aspects and types in various locations over the world, particularly in places that have a high level of solar insolation (Figs. 7.3 and 7.4).

The aim of the surveys is to emphasise the critical design concepts in different places and provide an indication of the characteristics of these global system designs. A toplight system can be uniformly spread over a wide area and has a very effective sustainable design. Table 7.1 shows the particular tasks and conclusions localised for each system.

Generally, the above-mentioned studies indicate that toplight systems are practical and can complement electric lighting in various climatic conditions. These systems bring the lively quality of the outside environment indoors. The interactions with sun and cloud movements create a more stimulating environment than constant interior lighting. The dramatic, ever-changing sources of light level produced in these systems elicit a pleasant response from people and help people perceive and enjoy colour, texture, and shape. Despite these benefits, a daylighting designer needs to bear in mind several critical considerations when designing toplighting systems. These considerations are visual and thermal comfort, heat loss and heat gain, seasonal and daily shifts in daylight availability, and integration with the electric lighting system, roofing system, and HVAC design [28].

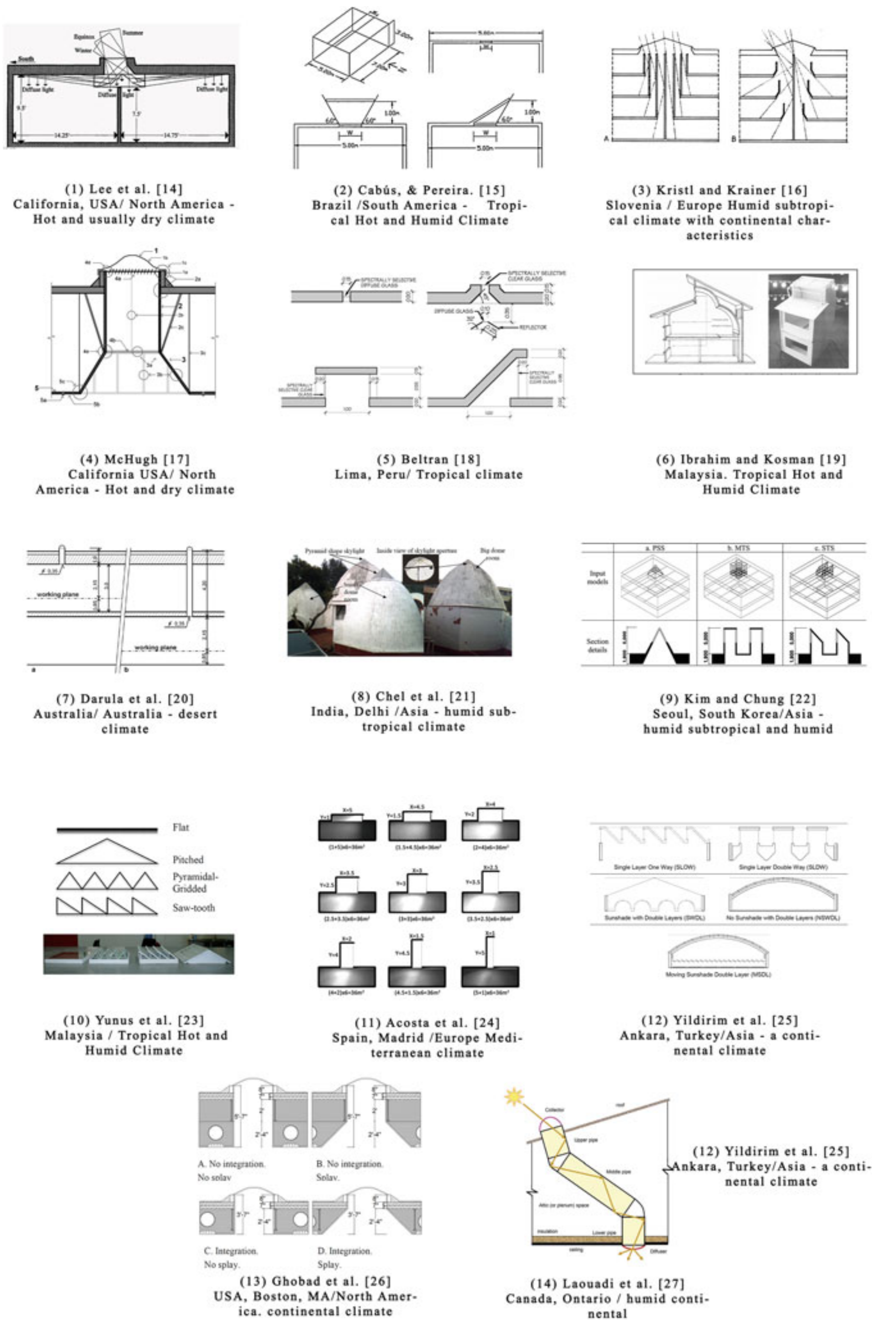

Fig. 7.4 Toplighting systems by different researchers globally

Table 7.1 Summary of Figs. 7.3 and 7.4

Authors	Types	Designs	Conclusions
Lee et al. [14]	Skylight	The skylight design comprises three systems: skylight opening and light well, a reflector array, and a lower diffusing panel *Location: California, USA/North America—Hot and usually dry climate*	The design improves light redirection and achieves balance throughout a deep perimeter space by employing geometry and a special prismatic film to reflect direct sunlight throughout the year
Cabús and Pereira [15]	Skylight, monitor, and sawtooth roof	The study compared three toplighting methods. Sunlight and skylight, along with shading devices, were employed to create various models *Location: Brazil/South America—Tropical hot and humid climate*	The study concluded that opening systems are able to capture and redistribute some direct sunlight and can produce well-lit spaces with minimum heat gain. Internal surface reflectance was found to be important for work-plane illuminance
Kristl and Krainer [16]	Light wells	Three simple light wells (8 m height) were designed according to three types: individual, semi-individual (where the light well is divided into two individual light wells by a vertical reflecting wall), and combined (where all the apartments are illuminated by a common light well) *Location: Slovenia/Europe—Humid subtropical with continental climate*	The findings revealed that the optimum use of natural daylight is achieved by using semi-individual light wells with wide upper and narrow lower parts, into which the reflecting wall is placed. In this method, the topmost floors are lit mostly by direct light, whereas the ground and first floors are illuminated by both direct and reflected light from the inclined mirrored wall
McHugh et al. [17]	Splayed skylight wells	This study considered two parts of light wells: splay and throat *Location: California USA/North America—Hot and dry climate*	The design allows daylight to spread as broadly as possible whilst reducing glare from overly bright surfaces
Beltran [18]	Skylights	This study examined the daylight performance of traditional and innovative toplighting systems: skylights with diffusing glazing, sawtooths, clerestories, roof monitors, skylights with splayed wells, and reflectors and diffusers beneath the aperture. All these designs involve high-performance glazing *Location: Lima, Peru—Tropical climate*	The findings indicated that skylights with reflectors provide the best overall daylight and thermal performance among all the systems. Skylights with reflectors provide uniform light all throughout the space (500 lux). Roof monitors introduce the most uniform and highest illuminance levels.

(continued)

Table 7.1 (continued)

Authors	Types	Designs	Conclusions
			Toplighting systems with sufficient solar control and proper use of reflective surfaces can deliver good daylight illumination and conserve energy
Ibrahim et al. [19]	Monitor	The first prototype involves a single-curved ceiling, and the second prototype has a double-curved ceiling. Two approaches were adopted to test the potential of the models in illuminating indoor spaces *Location: Malaysia—Tropical hot and humid climate*	The appropriately designed roof opening with a light shelf and curved ceiling can distribute daylight illuminance in the internal zone. The model designs for daylighting proposed in this study can potentially be adopted in Malaysian houses
Darula et al. [20]	Tubular light	Original tubular light guides with a transparent hemispherical cupola positioned on a roof gather all sunlight and skylight obtainable at ground level throughout a year *Location: Australia/Australia—Desert climate*	The study found that the luminous effectiveness of tubular light guides in tropical regions is high because of long sunshine durations and dominant high solar altitudes. However, in areas with a temperate climate, these two features are poor, particularly during cold seasons
Chel et al. [21]	Skylight	This study examined a mathematical system for an existing skylight combined with a dome-shaped indoor mud house to evaluate the daylight factor grounded on the alterations in the prototype presented by CIBSE *Location: Delhi, India/Asia—Humid subtropical climate*	The proposed prototype defines the daylight factor and indoor illuminance of a building with a skylight, which almost meet those in the investigational findings at various vertical levels of the work plane
Kim and Chung [22]	Skylight: pyramid, monitor and sawtooth	Twenty scaled prototypes were constructed in this research to estimate the daylighting performance. A reflectance value of 70 % was applied for the light well and ceiling, 50 % for the walls, and 30 % for the floors *Location: Seoul, South Korea/Asia—Humid subtropical and humid continental climate*	Monitor toplight models were confirmed to be highly effective in cutting off direct sunlight. Sawtooth guarantees stable daylighting performance. These models were designated as attractive replacements for the current skylight system

(continued)

Table 7.1 (continued)

Authors	Types	Designs	Conclusions
Yunus et al. [23]	Skylights	This study examined the effects of roof forms and internal structural obstructions on daylight levels in atria. Four types were tested in the analysis: structured flat roof, structured pyramidal gridded roof, structured north- and south-facing sawtooth roof, and structured north-east-sloping glazed pitched roof *Location: Malaysia—Tropical hot and humid climate*	The inclined roof exhibits various patterns of daylight reduction levels. For high angles, complicated roof profiles, and east- and west-facing surfaces, the daylight level decreases to more than half of that in an unobstructed atrium. A west-facing atrium receives more light at all floor levels. During the brightest time of the day, daylight reduction by the structured sawtooth roof is lower than that by the others
Acosta et al. [24]	Light-scoop skylights	Different types of light-scoop skylights were tested in different room sizes. A light-scoop skylight that is 6 m long and with variable heights of 3, 4.5, and 6 m was placed in the centre of the roof *Location: Madrid, Spain/Europe —Mediterranean climate*	The study found that for this type of skylight, a height/width ratio of approximately 4:3 is the best model to ensure maximum daylight levels in a space under overcast sky conditions
Yildirim et al. [25]	Roof skylight systems	Five roof skylight systems were considered. These five are single-layer one-way roof skylight system, single-layer double-way roof skylight system, sunshade with double layers, no sunshade with double layers, and moving-sunshade double-layered roof system *Location: Ankara, Turkey/Asia—Continental climate*	The results revealed that light should be restricted to avoid glare. When sunlight is limited, light should be admitted at a higher rate. The double-layered roof system, which delivers uniform and sustainable lighting in all conditions, demonstrates the best performance compared with the other four roof skylight systems
Ghobad et al. [26]	Light well	This paper focused on four light wells and ceiling geometries. The glazing area, expressed as the skylight to floor area ratio (SFR), was 5, 6, 7, and 8 %. The transmissivity of the glazing was 40 and 54 %	The study showed that a splayed ceiling integrated with a duct in the structural volume reduces building costs, allows the roof to be lowered, and decreases unwanted thermal gains.

(continued)

Table 7.1 (continued)

Authors	Types	Designs	Conclusions
		Location: Boston, MA/North America—Continental climate	The quantity of useful illuminance on the task surface is improved, the variations in illuminance on the task surface are reduced, and the potential light is boosted
Laouadi et al. [27]	Tubular daylighting devices	The study assumed that tubular daylighting devices transmit sunbeam light, skylight, and surrounding reflected diffuse light. The transmitted and absorbed luminous fluxes rely on device geometry structure and diffuse light intensities *Location: Ontario, Canada—Humid continental*	The study concluded that the devices include three various units (upper, middle, lower), with elbows joining them at the roof and ceiling levels. The device collectors may take a conical or hemispheric shape or a combination of both. Collector glazing may comprise diffusing elements, reflectors, prisms, or multi-panes distributed along the glazing surface. The ceiling diffusers may be hemispheric or planar and could have multiple prismatic or diffusing

7.3 Daylight Design and Outdoor Environment

The following statement by Edwards and Torcellini [3], '*the physics of daylighting has not changed since its original use, but the building design to use it has*', indicates that one must understand that the light that originates from the sun and sky is fundamental to understanding any building system because the sun and sky provide specific qualities and quantities of light. However, their effects differ with the time of day, climatic conditions, and season of the year. Understanding their behaviours in a particular local climate affects the design for a specific place [28].

According to Baker and Steemers [29], each sky condition has different characteristics (Fig. 7.5).

(i) **Clear sky**: Luminance varies over the azimuth and altitude. It is brightest around the sun and dimmest in the opposite direction; the brightness of the horizon lies in between. On a clear summer day, the outside light levels could reach as high as 100,000–140,000 lux on a horizontal surface.

(ii) **Intermediate sky**: To some degree, this sky is a hazy variant of the clear sky. The sun is not as bright as that in the clear sky, and brightness variations are not extreme. CIE defines it as having a cloud coverage of between 30 and 70 %.

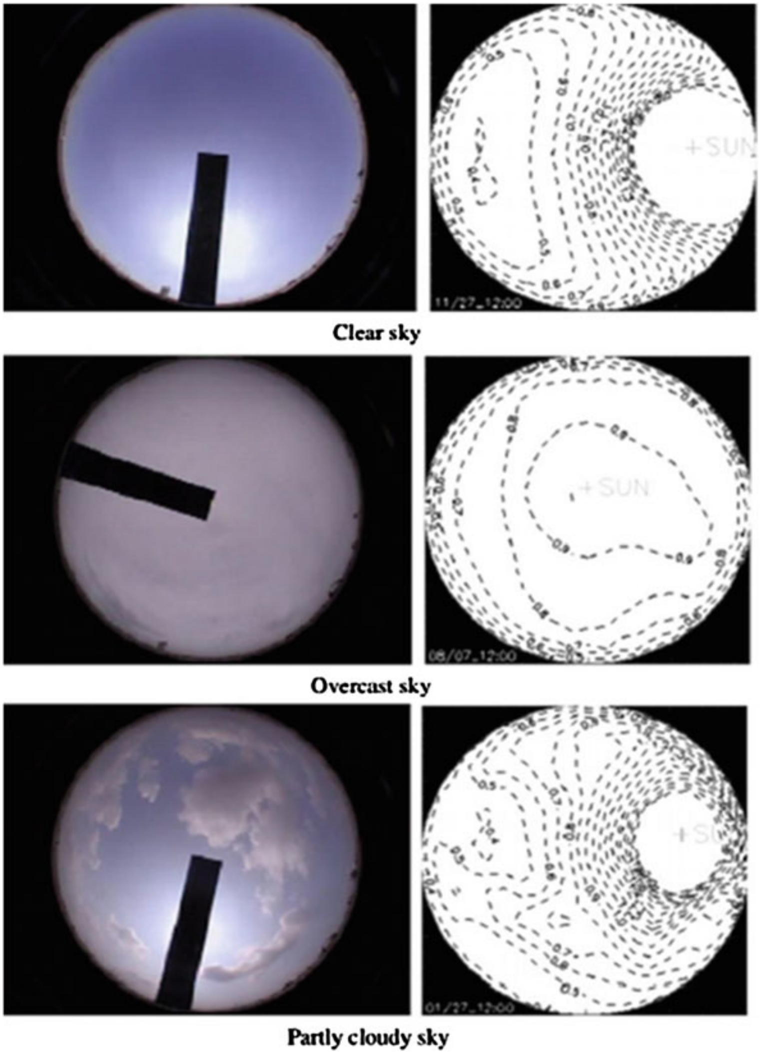

Fig. 7.5 Example of clear, overcast, and partly cloudy skies identified based on the CIE description [30]

(iii) **Overcast sky**: The luminance of the sky changes with altitude. This sky is three times as bright in the zenith as it is near the horizon. On a dark overcast day, this sky might fall below 20,000 lux (depending on the latitude).

The natural light that comes into a building originates from three sources, namely directly from the sun (sunlight), light diffused by the Earth's atmosphere (daylight), and light reflected from the ground or other surfaces (also called daylight). The general assumption is that sunlight and skylight can be utilised synonymously. In fact, these terms are entirely different because each has unique physical characteristics and different effects on skylight roofing systems. These differences include intensity, diffusion (scattered), and colour. Two important factors, namely luminance and illuminance, should be considered in the evaluation of these types.

Fluctuations in sky luminance are affected by the weather, season, and time of day and are difficult to codify. However, CIE published a calculated method (International Recommendations for the Calculation of Natural Daylight in 1970) that employs illumination as a set of curves to identify the time period during which daylight is likely to meet the lighting requirements of a building (Fig. 7.6). This method determines the percentage of required exterior illumination on the horizontal plane approximately between 07:00 and 17:00 h at different latitudes. In reality, this method does not consider specific site conditions, overshadowing by hills, trees or buildings, neighbouring surfaces, or the design of the building itself [10].

7.3.1 Natural Light Types

In actual scenarios, sunlight and daylight have entirely different characteristics. Sunlight represents a point source of light generally referred to as a beam for the reason that it is highly directional. This beam of light casts shadows and is an extremely intense source of light; it can deliver as much as 50,000 to more than 100,000 lux of illumination. As mentioned previously, sunlight differs depending on the location and time of year. The intensity of light is extremely high at noon in the tropics when the sun is overhead and at high altitudes with thin air. However, it is less intense in the Arctic because of the low angle of the sun.

Light from the sky is more diffused and scattered in all directions; it does not cast any shadow. It comprises the light from both cloudy and clear blue skies. Most people are surprised to know that cloudy skies are brighter than clear blue skies. The brightness of cloudy skies varies and relies on cloud thickness and colour. Generally, total cloud cover is likely to form an extremely uniform lighting condition, whereas a clear blue sky is unpredictably non-uniform because it is brightest around the sun and darkest at 90° opposite the sun's location [12]. These differences create various characteristics of colour temperature; a clear blue sky delivers a cool colour temperature of approximately 10,000 °K (9726 °C), and a cloudy sky delivers a warmer colour temperature of approximately 7500 °K (7226 °C). Identifying the percentages of these properties at specific locations would help estimate the amount of illumination available for skylight [28] (Table 7.2).

Given that climate conditions directly affect daylight levels, the environmental factors that affect the qualities and quantities of daylight must be understood to identify the type of system to be used. Table 7.3 provides a summary of the most important issues related to natural light as indicated in the studies of Ruck and Aschehoug [12] and Phillips [1].

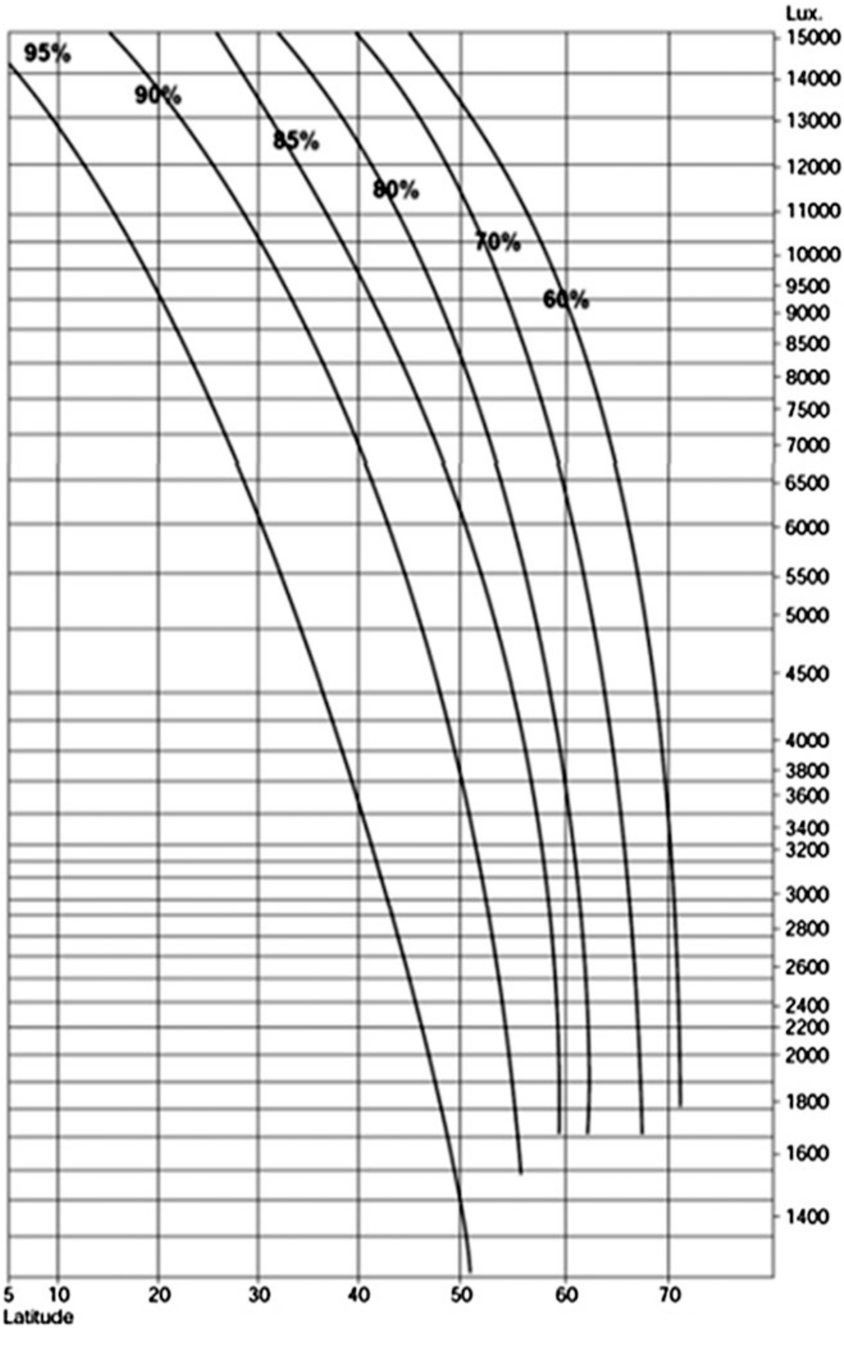

Fig. 7.6 CIE calculation method that employs a set of curves to identify the amount of lux in a time period

Table 7.2 Daylight characteristics [28]

	Light direction	Illumination fc	Brightness cd/m^2	Colour temp.	Colour description
Sun at midday	Beam	8000–10,000	1,600,000,000	5500 K	Neutral
Sun at horizon	Beam	3000–8000	6,000,000	2000 K	Warm
Clear sky	Diffuse	1000–2000	8000	10,000 K	Bluish
Cloudy sky	Diffuse and Beam	500–5000	2000	7500 K	Cool

Table 7.3 Important issues related to design with natural light

Factors	Description
Change/varity	Daylight change from day to night, changes associated with variations in the weather (from bright sunny days to dark and cloudy or rainy days) as well as season. Daylight direction on overcast and cloudy days remains changeable, although the light is more diffused than that on a clear day. On overcast days, daylight is uniform but varies in absolute brightness from sunrise to sunset
Orientation	The orientation of sunlight during a year is changeable. For instance, in Malaysia, January with its low inclination in the south is different from April, which is overhead, and June, which has low inclination in the north. The characteristic of each month is unique because every period in a year reflects a specific sun path
Sunlight effect	The effect of sunlight in hot climates varies according to cloud cover and weather conditions and influences the distribution of solar radiation as direct or diffuse, which is changeable in a day and a year
Colour	Daylight colour varies from morning to evening and with variations in weather patterns and sky conditions. The sun at midday provides 5500 K neutral colour temperature, whilst the sun at the horizon provides 2000 K warmth. Vision is improved with good contrast, and the natural colour of daylight increases contrast

7.4 Evaluation

Toplighting systems provide additional daylight to a room throughout the year compared with vertically oriented openings. They are casting light over a space in a uniform manner and with less likelihood to be blocked either internally or externally. Each system has advantages and disadvantages and performs differently. The review shows that system types and models vary. However, when sky conditions are considered, the design could become more effective.

The studies also showed that different daylight conditions (either clear or cloudy skies) have an effect on the design of toplighting systems. The most important consideration in these designs is how to deal with direct sunlight. The investigations performed by above-mentioned studies provide techniques that aid in establishing effective designs under these conditions.

On the other hand, in most cloudy conditions, the design requires the distribution of natural light to indoor places where direct sunlight is unavailable. In this condition, to deliver a sufficient amount of daylight, the system needs to be relatively large (skylights) or short (light tube or pipes) and placed in a position that helps capture most of daylight during a day. Various designs, such as pyramid, bubble, arched shaped, monitor, and sawtooth, are effective in bringing daylight during the early morning or near evening, with approximately 5–10 % at these critical low angles. Skylights, atria, light tubes, and ducts applied to a horizontal roof are independent of orientation and offer more design independence compared with other designs. During overcast days, horizontal opening systems supply the highest level of light under the brightest environments. In addition, solar heat gains tend to be minimum than anticipated because of the stratification of heated air in the system wells.

However, under sunny conditions, direct sunlight can be extremely bright that the quantity of incident light striking on a small opening is almost enough to deliver sufficient daylight levels in large indoor places. Thus, these opening designs are considered weak, causing glare and overheating, particularly in toplighting schemes with horizontal glazing. Hence, vertical or near-vertical rooflights (e.g. clerestories, sawtooth or roof monitors, and light tubes and ducts) are often preferred for lighting in single-storey deep spaces.

Though all these systems remain inappropriate for the tropics because of the significant impact of solar radiation. Therefore, these systems should be integrated with shading, glare protection, proper use of reflective surfaces, splaying and wells for the skylight, and a double-layered roof system to improve the design of monitor, sawtooth, and atria using different geometries, roof angles, orientations, and complicated roof profiles. Furthermore, optimising the use of diffusing elements, such as light ducts and tubes using reflectors, prisms, and multi-panes, is helpful in distributing daylight along the glazing surface. These systems can deliver good daylight illumination and reduce relative heat loss and heat gain.

Generally, the study opens the possibility of delivering an overall picture of the hidden issues that required to be highlighted in the application of toplighting systems. Understanding the technical parts is very important. Al-Obaidi et al. [31] proposed an approach called ESI to identify the controlling factors in a design. Based on the evaluation, it can clearly be noticed that each climate condition adapts with specific design models. For instance, it was noticed that for tropical climate such as in Malaysia, it is very difficult to apply simple models of skylight due to environmental restrictions.

Supporting the above statements, there are several applications of skylight systems in Malaysia which are mostly limited for commercial and industrial buildings. Al-Obaidi et al. [6, 8, 32, 33] found that conventional toplighting system represents inappropriate approach for low-rise buildings. Al-Obaidi et al. [32] proposed a design entitled innovative roofing system (IRS) that dealt with many factors to overcome this issue such as glazing materials, optical features, thickness and layers, and colours of internal walls inside the system. Furthermore, a study by

Munaaim et al. [34, 35] used a fibre-optic technology as a daylighting system in Malaysia. The application was found to be totally dependable on the sky conditions. The findings showed that system's performance was controlled by environmental factors. Accordingly, it is found that the selection of these systems essentially requires a clear understanding of the mechanism of capturing the light with an interaction with outdoor environment before evaluating the architectural criteria.

Considering that toplighting systems have significant application potentials, five simple decisions on toplight design can be established whilst bearing in mind that all other factors need to be considered to obtain a holistic approach towards passive design. Espiritu et al. [36], Heschong and Resources [28], Muneer and Kinghorn [37], Ruck and Aschehoug [12], Phillips [1], Kittler et al. [38], and Al-Obaidi et al. [32, 33] provided an exhaustive literature review and published a set of guidelines for lighting design for energy conservation. The five decisions are summarised below.

1. A decision should be made regarding the placement of the building whilst bearing in mind the sun path, climate condition, skies type, orientation, and location of existing buildings or site characteristics. The landscape of a green field or urban situation is important.
2. A person receiving more than 1000 lux from natural daylight for less than one hour a day is not receiving a sufficient amount to preserve optimal mood. A standard office worker could spend 50 % or more of his time in environments of 0.1 to 100 lux. These issues should be addressed by rethinking the environment of building interiors.
3. The building design, room dimensions, heights, and subdivisions should be determined in consideration of the present and future needs of users. Room height and surface reflectance represent a key decision; they specify the daylight penetration, desirable overall room depth, and building costs to achieve high overall efficiency.
4. The technical issues related to opening size and disposition, specification for the nature of the glass, transmission value, and other characteristics (e.g. window/floor area ratio) should be reviewed. With regard to skylight types, Christoffersen [39] found that opening ratios above 25 % significantly reduce net energy savings for buildings. De Montfort University's Institute of Energy and Sustainable Development demonstrated that installing between 15 and 20 % rooflight can significantly reduce building CO_2 emissions. In fact, these percentages allow quality daylight to be transmitted and maintain the potential for large overall energy saving because of reduced lighting loads. However, these ratios vary according to place and location.
5. Controlling daylight levels by different techniques, such as orientation, angles, reflectors, prisms, and multi-panes, manages the sunlight amount and glare and controls the heat gain of the interior; hence, energy is saved and cooling and heating demands are reduced.

Although the five decisions outlined above are considered essential, each point should be associated with the other criteria for a comprehensive design and to meet durability requirements. Understanding these points would help designers relate overall passive design to sustainability.

7.5 Conclusion

This review highlights the most optimal requirements of passive toplighting systems by comparing several passive systems globally. The study found that this area of investigation is completely important to support the sustainability and resilience approaches that depend on the sky dome. The review realises that system type, sky condition, and human comfort represent the significant factors for a passive assessment. The review shows that a purely energy-efficient scheme, which does not pay attention to environmental needs, might become unproductive. Adopting these schemes may be faulty without balancing the total design requirements, especially those related to a comfortable and pleasant environment.

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Chapter 8
Polychaetes as Ecosystem Engineers: Agents of Sustainable Technologies

Widad Fadhullah and Muhammad Izzuddin Syakir

Abstract Polychaetes are the so-called ecosystem engineers as they are constantly feeding, digging, burrowing, irrigating, reworking and ingesting particles in the sediment and near to the sediment–water interface. Their behaviour through bioturbation has significant impact on sediment biogeochemistry, in processing highly enriched sediments, and provides tolerance towards hypoxia and highly polluted areas. In this paper, the review introduced briefly about the distribution of polychaetes in the world, explained its role in tackling environmental issues such as detoxifying inorganic contaminants into less toxic compounds, processing organically enriched sediments via their digestive system and overcoming hypoxia and anoxia cases plus sulphidic conditions. All these criteria enable polychaetes to be agents of sustainable technology. Then, the focus is emphasized on the lack of studies about polychaetes in Malaysia. Increasing number of studies is currently in place to document their distribution in Malaysia. Research that addresses how polychaete processes their waste and how their body adapts to various environmental degradation would be vital as key towards sustainability in environmental applications.

Keywords Polychaetes · Ecosystem engineers · Sustainable technology · Environmental sustainability

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8.1 Introduction About Polychaetes

Polychaetes or multi-segmented worms play a significant role in ecosystem functioning and services. Fish anglers appreciate their existence by searching and collecting them to be used as bait [1]. It is also used as feed of prawn broodstock in aquaculture, particularly *Penaeus monodon* due to its high levels of essential fatty acids for reproduction and protein content essential for amino acid and vitamin sources [2]. Polychaetes are the major dominant organism found in sand and muddy habitats and are ecologically significant functional component of coastal ecosystems [3]. Worldwide, there are over 80 families of polychaetes [4]. Table 8.1 listed

Table 8.1 Selected families and species identified by polychaetes taxonomist (adapted from Read and Fauchald [4], Idris and Arshad [48])

No.	Family	Species	Distribution	Common names
1	Acoetidae	*Eupanthalis perlae*	Pacific Ocean, Panama	–
2	Capitellidae	*Capitella capitata*	India, UK, Black Sea, Denmark	Gallery worms
		Notomastus latericeus	Lagos Lagoon, Nigeria	Bristle worms
		Notomastus abyssalis	Gulf of California, USA	–
		Arenicola marina	North Sea to Oresund, Arctic to Mediterranean	Lugworms
3	Nereididae	*Nereis virens*	North Sea, German Bight	Sandworms
		Nereis diversicolor	North-east Atlantic	Ragworms
		Nereis succinea	Atlantic coast of USA	Common clam worms
4	Eunicidae	*Eunice colombia*	Southern Caribbean	–
		Eunice dubitata	North Atlantic Ocean	–
5	Glyceridae	*Glycera alba*	Black Sea	Bloodworms
6	Nephtyidae	*Nephtys californiensis*	Brazilian Coast	Shimmy worms
		Nephtys australiensis	Australian waters	Nephtyid worms
7	Onuphidae	*Diopatra papillata*	Gulf of Mexico	–
		Onuphis texana	Gulf of Mexico	Onuphis worms
		Diopatra neapolitana	Rio De Aveiro, Portugal	Solitary Tube Worms
8	Sabellidae	*Branchiomma nigromaculatum*	Caribbean Sea	Fan worms
9	Spionidae	*Streblospio benedicti*	North Sea	Bar-gill mudworms
10	Syllidae	*Syllis cornuta*	Teluk Aling, Penang, Malaysia	Marine bristle worms
11	Tomopteridae	*Tomopteris mariana*	Straits of Malacca	Plankton worms

some of the different families and species of polychaetes that have been identified by taxonomists.

These worms act as the primary or secondary consumer in the food webs and are categorized as detritivores. They can be found everywhere in the oceans, near to rocky shores, freely swimming in the water and in the sediments. Therefore, polychaetes play a major role in sediment biogeochemical processes and sediment stability. These organisms tend to be the initial macrobenthic colonists after any physical and/or chemical disturbance, and a large number of taxa inhabit the most stressed regions of a pollution gradient [5].

8.2 Ecosystem Engineers

Ecosystem engineers reflect organisms that may change, modify, maintain, or create habitats within its surrounding [6] via its feeding behaviour, their metabolic activities and the unique characteristic that they possessed. Ecosystem engineers comprise of organisms that can be found abundantly in nature, freely available and is easy to handle. Any organisms that can alter their physical surrounding can be called ecosystem engineers such as bivalves, crabs, ants, porcupines, rodents and polychaetes. Our study only focuses on polychaetes as ecosystem engineers in the coastal, estuarine and marine ecosystem. The purpose of this review was to (1) explain the marvels of polychaetes by describing how the polychaetes process inorganic and organic contaminants, (2) summarize the available literature for tolerance of polychaetes to hypoxia and anoxia events and (3) review the available literature about polychaete studies in Malaysia and highlight the needs and direction for future research. The major literature sources for this review were derived from the published journal articles. These documents included geochemical studies, biological/microbiological studies and ecosystem/ecology scope of studies. This review appears to be the first in documenting the current state of the art of polychaete studies in Malaysia.

8.3 The Marvels of Polychaetes in Processing Contaminants

The physiology, morphology, digestive and excretion mechanisms of the polychaetes are unique by providing multiple benefits to the coastal, estuaries, swamps and mangrove ecosystem. Polychaetes are among the organisms that spend most of its time living in the interstitial spaces in burrows or tubes, or moving freely through the sediment. They consistently alter the structure of the sediment by mixing, sorting and aggregating small particles into pellets and by pumping water into and out of the seabed through the action of bioturbation. These organisms are capable of modifying the biological and physicochemical characteristics of sediments through their circulatory, respiratory and excretory behaviours [7].

Bioturbation plays an important role in oxygenizing the bottom of sediment, affecting the biogeochemical processes involved within the sediment and at the sediment interface, and removal of metabolites up to the sediments surface [8]. Bioturbation functional groups can be described as biodiffusers, conveyors, regenerators and gallery-diffusers. Biodiffusers move particles in a random manner over short distances, while gallery-diffusers excavate burrows deeper in the sediment and moved particles from the surface to the bottom of the burrow. Michaud et al. [9] found that between the effect of biodiffusers, *Macoma balthica,* and the gallery-diffusers, *Nereis virens,* on oxygen uptake, the periodic ventilation of Nereis stimulated more oxygen to the sediments. Burrow construction and renewal of burrows by muscular movements of the body promote exchange of solutes between sediment and water.

Conveyors can be divided into upward and downward conveyors. Upward conveyors moved vertically by transporting particles from the deeper parts of the sediment to the sediment surface. In contrast, downward conveyors take up food on the surface and get rid of them as faeces deeper in the sediment [7]. The polychaete, *Capitella capitata* is known as a conveyor while *Hediste* or *Nereis diversicolor* is a regenerator [9]. A regenerator constantly digs burrows and brings sediment from the deeper depths to the surface. The burrows also function as a mechanism to protect the regenerators from predation and adverse environmental conditions [7]. Figure 8.1 shows the different bioturbation functional groups as adapted from Kristensen et al. [7] and Francois et al. [10].

The effect of reoxygenation alone and a combination of both reoxygenation and bioturbation of the polychaete, *Marenzelleria neglecta,* were studied by [11]. Reoxygenation alone has no significant effect in releasing organic contaminants,

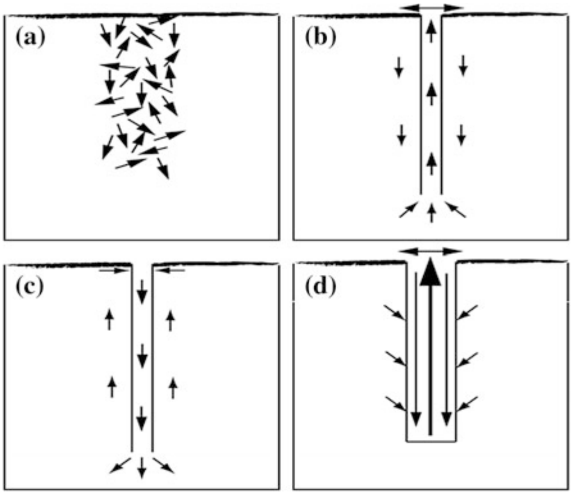

Fig. 8.1 Bioturbational functional groups. **a** Biodiffusers. **b** Upward conveyors. **c** Downward conveyors. **d** Regenerators [7, 10]

polychlorinated biphenyl (PCBs) and persistent organic pollutants. However, the bioturbation effect by *M. neglecta* stimulated the release of soluble PCBs and pesticide residues. Bioturbation stimulated reintroduction of contaminated particles to the sediment–water interface and oxygenation of deeper sediment layers, which in turn allows desorption of PCBs and further desorption by the gut passage.

The particle mixing, solute transport and microbial reaction rates were also different depending on benthic assemblages associated within the sediments. Bioturbation impacts were influenced by different feeding modes. This is shown by *Marenzelleria viridis* particle mixing through its food searching near the surface. In contrast, the head-down deposit feeder, *Heteromastus iliformis* particle mixing, is more influenced by defecation at the sediment's surface. Solute transport of *M. viridis* was through advective diffusive transport from actively food searching, increasing pore water movements, whereas *H. illiformis* appears to have modest impact on particle reworking as well as microbial carbon oxidation [12].

Apart from that, polychaetes also play efficient roles in sediment biogeochemistry. Based on carbon and nitrogen fluxes by nereids, most of them are lost through metabolic processes of worms and bacteria, and via denitrification retained in the sediment or stored as undecomposed algae. Excessive carbon loss is by microbial mineralization processes, while for nitrogen, most are excreted as NH_4^+ by animals. Increase ventilation activity of *Nereis diversicolor* decreases the total sediment metabolism and ammonium concentration in pore water. On the other hand for *Nereis virens*, they function in decreasing organic matter in sediments irrespective of the phytoplankton availability [13].

Nereis bioturbation increases oxygen and ammonium fluxes from the sediment to the water column. The activity of Nereis burrow construction and irrigation activities contributes towards pore water flushing and alters the bacterial mineralization, which in turn provides fresh organic matter and electron acceptors to the sediment. Moreover, transport of phosphate from the sediment to the water column is also enhanced, whereas in contrast, nitrogen was lost through stimulated denitrification of bioturbated *Nereis* [14].

The bioturbation effect of polychaetes also aids in microbial processes. Mermillod-Blondin and Rosenberg [15] have reported that bioturbation modified microbial processes in the sediment depending on the hydrological characteristics of the system. In the diffusion-dominated system, invertebrate bioturbation can produce water fluxes at the sediment–water interface that may strongly influence microbial processes. In the advection-dominated system, invertebrate bioturbation can only modify the water circulation.

A study by Madsen et al. [16], on impact of *Capitella* sp. I on microbial activity in fluoranthene-contaminated sediment, shows an increase of oxygen uptake and total carbon dioxide production in cores with worms in it. *Capitella* sp. I can promote polycyclic aromatic hydrocarbon (PAH) degradation from microbial activity by enhancing oxygen fluxes, but there is also possibility of pushing PAH deeper inside the sediment which is unreachable by the bacteria to process it.

The carnivore, *Sthenelais* sp. from the family Sigallonidae, showed an increasing number in response to accumulation of petroleum hydrocarbon on the sediment of

Gulf of Mexico. This suggests that carnivorous species are more immune to these stress compared to the other polychaete assemblage, comprising of scavengers and omnivores [17]. A biomarker study using *Nereis diversicolor* exposed to benzo{a} pyrene, a representative of PAH contamination, was conducted under laboratory conditions [18]. They have found that the antioxidant enzymes, catalyse, glutathione peroxidase, glutathione reductase and glutathione-S-transferase are responsible in the detoxification and biotransformation process of polychaetes, particularly of ragworms or *N. diversicolor*.

Dean [19] has reviewed about polychaetes function as an indicator of marine pollution. Different polychaete species have different tolerance to heavy metal pollutions. *Capitella capitata*, *Polydora* spp. *and Nereimyra punctata* were found to be the most in numbers at highly polluted areas. They are known to be indicators of polluted condition. Sensitive species which are found in unpolluted areas are *Glycera alba*, *Anabothrus gracilis*, *Pholoe minita*., *Capitella setose*, *Lumbrinereis* spp., *Terebellides stroemi* and *Scalibregma inflatum*. Polychaetes have the capability to detoxify metals which may be ingested from their food intake. Their gut is responsible in converting the metals into less toxic forms which will not affect the polychaetes health [20]. Biomarker study on the species, *Eurythoe complananta,* has been used as an indicator species towards elevated copper concentration. The biomarkers, which are biochemical responses to the oxidative effects of pollutants, malondialdehyde and antioxidant enzyme glutathione reductase were used on *E. complananta*. There was an increase in malondialdehyde while a decrease in the enzyme glutathione reductase, which acts as a free radical scavenger in the detoxification of contaminants [21].

8.4 Tolerance of Polychaetes to Hypoxia

Apart from its adaptive behaviour in processing various contaminants, polychaetes are also highly tolerant species towards oxygen depletion that may develop into hypoxia and anoxia. In sea water, hypoxia is defined as dissolved oxygen (DO) concentrations below $\sim$25 % of water oxygen saturation ($\leq$2 ml of O_2/l, $\sim$2.8 mg O_2/l) [22], whereas anoxia is defined as zero oxygen concentrations [23]. Hypoxia is influenced by natural phenomenon of the system itself, by human influences or as a result of both natural and **anthropogenically induced processes** [24]. Naturally occurring hypoxia is associated with water column stratification, which restricts water exchange in natural intrusions or upwelling of shelf systems, in silled basins and fjords such as Black Sea [25]. Human influences on coastal hypoxia are contributed by growing agricultural and industrial development which exerts increase amount of nutrients in water bodies, accumulation of pollutants and modification of the natural status of estuarine ecosystem [24]. The phenomenon of global warming is also one of the factors causing hypoxia by reducing oxygen solubility and degassing of oxygen in estuaries. Increased temperature will likely affect the responses of marine benthic organisms to hypoxia because metabolic rates increase exponentially with temperature [26]. Furthermore, stratification in the ecosystem is also enhanced and wind patterns are changing, influencing the transport and mixing of oxygen within an ecosystem [27]. Changes to the hydrological system may also affect nutrients and organic matter delivery [28], which may further exacerbate the occurrence of hypoxia. Reviews about hypoxia, the factors that caused its occurrence [24], effect of hypoxia to marine invertebrates [25] and prevention of hypoxia cases were already covered by other authors [23]. This review solely discusses the studies of hypoxia to polychaetes. Hypoxia causes mortality, changes in activity level [29], reduced abundances, diversity and biomass [30] and affected their growth and survival. Nevertheless, some species may tolerate the hypoxic events depending on the intensity, frequency and duration of the exposure. Sagasti et al. [31] stated that polychaetes, *Polydura cornuta* and *Sabellaria vulgaris*, in Neuse River estuary, North Carolina, can tolerate hypoxic episodes since it was only for less than a week during neap tides in the summer. The effect of tidal currents also reoxygenates the deeper waters during spring tides, causing only seasonal hypoxia. However, *S. vulgaris* was more abundant in higher oxygen areas, indicating species-specific effect on polychaetes. This is related to the different physiological adaptation between different taxa [31].

Intertidal nematodes survivals to anoxic events were also species-specific. Less tolerant species, such as *Daptonema setusum* and *Chromadora macrolaima,* were dominant in oxic conditions, but disappeared as the level of oxygen reduced. Highly tolerant species, *Metachromadora vivipara,* thrived in suboxic and anoxic conditions due to its ovoviviparous reproductive strategy by securing the survival and development of their juveniles [29]. Opportunistic polychaete sp., *Paraprionosporo pinnata,* survived low DO due to heavy recruitment after hypoxia and emigration of adults [32]. The polychaetes, *Marenzelleria viridis* and *Hediste diversicolor,* were able to reduce their metabolic rates, thus conserving energy, which is a credit for longer survival during anoxia [33].

According to Linke-Gamenick et al. [34], among three sibling species of Capitella, *Capitella* sp. I is the most tolerant species compared to *Capitella* sp. S and *Capitella* sp. M. Their differences from various geographical regions exhibit different physiological tolerances. *Capitella* sp. I as oxyregulators shows the highest tolerance to sulphidic and hypoxic conditions by maintaining aerobic metabolism in both conditions. It is also unaffected by oil pollutants due to the presence of a mixed-function oxygenase system, which functions in detoxifying aromatic hydrocarbons. The metabolic system reacts by transforming ingested fluoranthene into soluble excretory products after a few days of exposure.

The extreme tolerance of *Tubificoides benedii* in habitats with anoxia and high levels of hydrogen sulphide are related to the production of iron-rich mucus as a detoxifying mechanism of poisonous sulphide by trapping the sulphide in the mucus and then disposing them together with the papillae. Moreover, it has an effective blood circulation with a high oxygen affinity [35]. Similar adaptations were found by [36] for *Methanoacaria denrobranchiata* in hypoxic environment. Its respiratory adaptations include having high oxygen affinities, contains extracellular haemoglobin in its blood vessels, short diffusion distance across the gill epithelia, and the gills are hypertrophied, resembling vent polychaetes.

Effect of hypoxia (<1 mL O_2 L^{-1}) has caused polychaetes to move upward to the sediment surface [37]. Two examples of polychaetes, *Tubulanus* sp. and *Sipunculida* sp., showed movements and squirmed in place as captured by a time-lapse camera. The approach of the study which captured continuous and repeatable behavioural responses from species to community level aids in predicting potential future changes in benthic structure and ecosystem functioning.

Fluctuating changes in oxygen concentrations may influence sediment inorganic nitrogen cycling in estuaries. An opportunistic species, *Alitta* (*neanthes*) *succinea,* was used to measure the effect of its density and size to denitrification and sediment–water fluxes of inorganic nitrogen [38]. Under hypoxic condition, larger worms are more efficient in removing fixed nitrogen compared to smaller sized worm. These effects were attributed to the capability of larger worms to burrow deeper in the sediment and irrigate more water and solutes through their burrows.

Marenzelleria spp., an invasive polychaete species to the Baltic Sea, has been reported to tolerate low oxygen levels compared to the other native species. This species has also caused negative consequences to other native polychaete species such as *N. diversicolor* [39]. Norrko et al. [40] have studied the impact of this species to the sediment phosphorus dynamics. A positive impact was observed by ensuring the long-term phosphorus storage in the sediment. Iron hydroxide which binds phosphorus to the sediment prevents phosphorus release to the water column which may delay the occurrence of eutrophication. Through its bioirrigation activity, this species were able to improve bottom water oxygen conditions in coastal areas.

8.5 Polychaetes and Waste Management

Polychaetes have been reported to be in abundance at highly enriched areas by sewage, effluent discharges and organic waste accumulation. The presence or absence of specific polychaetes indicates the health condition of the benthic environment. Spionids and capitellids were found to be abundant in sewage-impacted site due to high organic matter content. *Boccardia proboscidea* is the dominant species in sewage-impacted site at Mar Del Plata, Argentina, due to ingestion of the film of the organic matter deposited at the surface. This small species is an opportunist with a short life cycle adapted to life in reducing sediments [41]. *Capitella capitata* were also found in high density at the site closest to the sewage discharge. This species can adapt in highly enriched organic sediments due to its adaptability to long-term anaerobiosis and its ability to detoxify sulphide to thiosulfate [42]. *Syllis prolix*, *S. gracillis* and *Leodamas uncinata* were found to be sensitive species towards sewage enrichment [41].

Polychaetes have been reported to feed on wastes (uneaten feed and faecal material) from aquaculture ponds. This factor may coin polychaetes as indicators of aquaculture system. *N. diversicolor* were used to feed on eel sludge and sea bream sludge [43]. Palmer [44] has used two polychaetes, *Perinereis nuntia* and *Perinereis helleri,* in sand beds receiving wastes from prawn farms. N. *virens* were found to be an excellent candidate for converting fish wastes to valuable biomass through an integrated aquaculture in land-based systems [45].

An invasive alien polychaete species, *Branchiomma bairdi,* was evaluated for its potential use for bioremediation by removing bacteria from the water column [46]. The findings showed that *B. bairdi* was able to digest bacteria such as *Vibrio*s and *Escheria coli* through its filter-feeding behaviour. This ability can help restore the water quality by removing pathogenic bacteria. This will in turn ensure the health of an ecosystem through sustainable environmental management.

In a tidal flat in Rayong, Thailand, accumulation of organic wastes as a result of intensive shrimp culture can affect benthic organisms and result in frequent blooms of phytoplankton. Benthic polychaetes were used to manage the organic waste accumulated in the sediments via organic matter decomposition. *Notomastus* sp. from family Capitellidae was found to strive in high organic enrichment sediments [47].

8.6 Polychaete Studies in Malaysia

We have touched about the role of polychaetes in processing organic contaminants, in sediment biogeochemistry and in waste management from other countries. So, how about the studies of polychaetes conducted in Malaysia?

Majority of the studies conducted on polychaetes in Malaysia focused on the ecological approach by documenting their taxonomy, distribution, diversity and their interrelation with environmental factors. New species are currently being discovered by marine ecologist in the field, and ongoing studies and research are continuously progressing towards collecting and identifying the available species in Malaysia. Although many polychaete species have been identified, their role in the environment is yet to be explored. This section only selects species that have been mentioned in the publications from the year 2012 and above.

As of the year 2013, 64 species from 31 families have been identified in Malaysia from the year 1866 to present. Out of these, the majority of polychaete species belongs to the family Nereididae, followed by family Capitellidae. Most of the earlier efforts were conducted by other nationalities, and up until now, no taxonomist exists in Malaysia. One of the polychaete species identified, *Halla okudai,* was the first to be reported in Southeast Asia, particularly at the Straits of Malacca. In addition, *Diopatra capleredii* were also identified and are harvested as baitworms along the west coast of Peninsular Malaysia [48].

Continuous taxonomy studies of polychaete species from the west coast of Peninsular Malaysia were carried out by Idris et al. [49]. Another species, *Marphysa moribidii,* was identified at Morib mangrove within 4.5 cm depth of the surface in the mangrove area with *Rizophora apiculata*, *Avicennia alba* and

Sonneratia caseolaris. This species were sold at MYR10 for 5–10 individuals among locals as baits throughout Peninsular Malaysia except Perlis.

Another interesting aspect on the ecology of these polychaetes is related to its distribution within polychaete reefs. The reefs were formed by accumulating organisms, rising from the seabeds that create solid structures from calcium carbonate tubes or cemented shell fragments. One of the reef organism builders is the polychaetes in Jeram, Selangor. Eight species from 6 families were identified, *Neanthes* and *Nereis* sp. from the family Nereididae, *Diopatra* sp. from Family Onuphidae, *Acholoe* sp. and *Malmgrenia* sp. from family Polynoidae, *Sabellaria* sp. from family Sabellaridae and *Loimia* sp. from family Teberrelidae. One species was unidentified from family Spionidae. The author proposed to gazette the Jeram Beach as a marine nature reserve in order to conserve its diverse species and magnificent ecosystem [50].

Gholizadeh et al. [51] have found that high percentages of sediment with grain size ≥125 μm in the coastal water of Pantai Acheh and Teluk Ketapang, Penang National Park, have an increased in macrobenthic (polychaetes) abundance. Spatial distribution of polychaetes was found to be related to the sediment particle size. The sediment type, whether it is sand or mud, and the polychaetes feeding type determined the distribution of the different families of these polychaetes. Polychaete families' distribution at the sampling stations near to the coast displayed change in sensitivity levels to pollution impact. It was observed that polychaetes from the family Spionidae, Nereidae and Nephtylidae were more dominant in station 200 m at Pantai Acheh, which was near to a mangrove forest. Teluk Ketapang, assumed to be minimally altered by anthropogenic stress, was occupied by family Spionidae, Hesionidae, Nereidae, Orbinidae and Nephtylidae. Out of all these families, polychaetes from family Nereididae were found to be the most abundant.

Shi et al. [3] have investigated the polychaete community structure in the seagrass bed of the Merambing and Tanjung Adang shoals, Johor Malaysia, and have determined the environmental variables that might affect the distribution and abundance of polychaetes. In the study, four parameters, pH, chromium, organic matter and percentage of clay–sand, were found to influence the polychaete community the most. Capitellidae, Spionidae, Cirratulidae and Nereididae were the dominant taxa at both sampling sites, possibly indicating that the Merambong and Tanjung Adang shoals were under stressed conditions due to environmental pollution. Out of all these studies in documenting the distribution and abundance in Malaysian coastal waters, the researchers have mentioned that scientific research regarding the polychaete community in Malaysia remains scarce and is in patches; thus, collective efforts are needed to fully document the taxonomy of these diverse creatures. The intentions of these researchers were to encourage more concerted efforts to spur further research, specifically on the polychaetes. These marvellous yet unnoticed creatures serve multiple functions in the ecosystem through nutrient recycling, hypoxia mitigation, organic contaminants processing and waste management. Thus, it would be a waste not to see the prospect of studying about polychaetes for the betterment of our precious nature.

Realizing the polychaetes contribution in processing the so-called wastes in the environment, a researcher has extended their study beyond taxonomy, diversity and abundance in Malaysia. A study by Baharuddin et al. [1] has tested the filtration capability of beach sand and construction sand with and without polychaetes in treating synthetic wastewater. Juvenile polychaetes of *Pereneis nuntia var brevicciris* were collected from Seagate, Penang and were manipulated in the laboratory for analysis. They observed that polychaetes definitely aided the filtration process in both types of sand as the organic matter in the sediment acts as a food source to them. Apart from that, DO, chemical oxygen demand (COD) and total suspended solids (TSS) were significantly reduced after filtration aided by the polychaetes. In terms of reducing DO, COD and TSS, the finding from this study offers better wastewater treatment approach from the conventional treatment of using settlement ponds.

8.7 Future Research and Recommendations

In relation to the diversity and taxonomy of polychaetes, efforts by researchers in temperate countries have provided a comprehensive list of polychaetes which can be found in the coastal and estuarine ecosystem. Continuous efforts are being done by researchers in tropical countries. Overall, *Capitella capitata* and *Nereis diversicolor* have emerged as the most tolerant species in highly polluted and organically enriched sites with mixtures of contaminants such as heavy metals, polycyclic aromatic hydrocarbon and sewage input. The specialty of polychaetes as an agent of sustainable technologies includes its apparent tolerance towards eutrophication that may in turn induce hypoxia and anoxia cases. Their role in processing high organic contaminants and recycling wastes in the sewage, sediment and aquaculture treatment serves promising venues for polychaetes to be used as a bioremediator in sediment cleanup. Invasive polychaete species do not give 100 % negative impact to the environment but may induce a positive effect such as in the case of *Marenzelleria* spp. In view of its importance in the environment, more study should be encouraged to mimic its credibility in detoxifying contaminants and how they digest and excrete these contaminants into fewer toxic components. The process of how it ingests particles, processes them within their digestive system and defecates them through decomposition in the burrows can be studied in order to apply the concept of a continuous cycle as one of the approaches for sustainable technology. Second, polychaetes can be used as a simple, natural and cost-effective measure to manage wastes and uphold sustainable technologies. The role of polychaetes in processing organic wastes from landfills should be encouraged to determine its potential. Leachate run-offs can also be examined with the presence and absence of polychaetes. Overall, polychaetes offer means of sustainable technology by learning through how they process the wastes, filter the contaminants that they ingest along with their food and withstand extreme conditions of high pollutants.

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Chapter 9
The Cooling Effects of Plants on the Built Environment

Nooriati Taib and Aldrin Abdullah

Abstract The rapid urbanization has resulted in high concentrations of high-rise building in the cities. The increase in high-rise building led to an increase in building's energy consumption that aggravates the urban heat island (UHI) effects and other environmental issues. The recent trend of "greening" building in urban areas allows an alternative way of reducing energy use in building and contributes to cooling effects. It is crucial in a hot and climate tropic where it is almost impossible to achieve thermal comfort outdoors, especially in hot seasons. Plants can be integrated in building design in several forms such as in a biofacade, a green roof and any landscape space. It is essential to understand the nature of plants and its characteristics in its localized settings to benefit the microclimate in the long run. Common issues of plantings in high-rise buildings are related to maintenance issues that involved cost, non-suitability of plants and under maintenance problem. The use of plants in buildings with proper planning and maintenance allows the future development to restore the loss of greenery in the concrete jungle development today.

Keywords Thermal comfort · High-rise building · Radiation · Transmissivity · Leaf area index

9.1 Introduction

There is currently a trend of incorporating greenery in high-rise buildings in cities around the world. This scenario can be observed especially in Asian countries such as China, Japan, Hong Kong, Malaysia and Singapore. Malaysia is among one of the most rapidly urbanizing countries in Southeast Asia. The high concentration of

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buildings and the loss of greenery in urban cities can aggravate the urban heat island (UHI) effect, therefore increasing the amount of energy used for cooling of buildings. One of the main challenges faced by the building industry today is to reduce the overall energy consumption as buildings are responsible for one-third of the total energy consumed in most major cities. This is especially the case for high-rise offices where the bulk of the maintenance cost lies. An energy audit conducted in 68 office buildings in Malaysia showed that energy consumption was mainly driven by air conditioning (57 %), followed by lighting (19 %), lifts and pumps (18 %) and other equipment (6 %) [1]. Previously, the average non-residential buildings in Malaysia consumed were between 250 and 300 kWh/m2 [2]. This highlights the need of more drastic strategies to conform to the inferred building energy index of 130 kWh/m2/year by Malaysian Standard MS1525 (2001). In tropical countries such as Malaysia, many high-rise office buildings are equipped with air conditioning systems, aimed at providing a comfortable working environment for its occupants. This is essential as people usually spend between 8 and 10 h daily at their work place. Office environments that are characterized by extreme heat, dim lighting and congested work areas are associated with stress at the workplace. It is therefore crucial to provide a comfortable working environment for thermal comfort purposes as well as for the psychological well-being of its occupants.

One of the ways to reduce the use of air conditioning in building is to encourage the use of non-air-conditioned space. In the high-rise development, transitional spaces have the potential to adapt passive design approaches. The passive design will allow natural ventilation and daylighting that helps to reduce overall building's energy consumption. Transitional spaces are known for its function as circulatory routes such as corridors, lift lobbies and atriums. Hence, these spaces can opt for passive design approaches, as it is more economical and practical. Introducing greenery in transitional spaces will help to improve the thermal comfort. Greenery can be in the form of gardens, green roofs, vertical planting or biofacade. Studies have proved that plants help to reduce the air temperature, reduce solar radiation, provide shades and eventually cool down the area. Today, the creation of landscape gardens in high-rise buildings is not only intended for aesthetic purposes. It is also meant for reducing building heat as well as providing psychological getaway spaces or a refuge space for the building's occupant. Past studies on thermal comfort in offices showed a positive relationship between nature and the psychological well-being of occupants in offices. The nature enhances emotional well-being, reduces stress and, in particular cases, improves mental health [3]. The conventional high-rise buildings have been criticized for separating their occupants from the natural environment. This is crucial for the high-rise dwellers where access to nature is limited. Landscape, in the form of sky courts and rooftop gardens, offers an opportunity for the building occupants to be in contact with nature above the ground level. It also allows social interaction among the building occupants and improves psychological well-being.

9.2 The Importance of Thermal Comfort

Achieving thermal comfort in high-rise buildings is more challenging compared to low-rise buildings, especially in the tropical regions. This is due to the fact that high-rise buildings are more exposed to climatic elements such as the wind, sun and rain as compared to low-rise buildings. In contrast, low-rise buildings are often surrounded by features such as trees, roofs or adjacent structures that can help to buffer them from the harsh climatic conditions. The environmental parameters that affect human thermal comfort and use of buildings are air temperature, air velocity, radiation and relative humidity. Achieving thermal comfort is vital particularly in the tropics due to the hot and humid climate conditions that often make it uncomfortable to stay indoors or outdoors. Unlike indoor spaces where the climate can be controlled, the surrounding environment influences the microclimate of the outdoor spaces. The microclimate is defined by the condition of solar radiation and terrestrial radiation, wind, air temperature, relative humidity and precipitation in an outdoor space. The microclimate components that can be modified through landscape design and that strongly affect thermal comfort are wind and radiation [4]. These two components are readily changed and can significantly affect human thermal comfort. In the existence of landscape, shading and radiation filtration by trees will affect the energy absorbed on the ground. Plants can also control wind through its velocity and directions. The wind passes through plants by means of obstruction, deflection and filtration may help to cool the area. On the other hand, air temperature and relative humidity that are measured at any given height above the ground level will be similar anywhere within the area of the same level due to the efficient mixing of air. Any temperature and relative humidity differences that may occur will dissipate quickly. Although there are no temperature differences horizontally within an area, temperature differences may exist with changes in height vertically, for instance, at different levels in the same building. A significant cooling in a person or evaporation accounts only when relative humidity is low and air temperature is high. Hence, radiation and wind play important roles in modifying the microclimate of a landscape.

However, modification of radiation has better contributions than wind in the open areas where it is highly exposed to the solar radiation. In the tropical climate, wind alone is not a major consideration in designing for thermal comfort. When a person's body temperature is nearly the same as the air temperature, wind becomes inefficient for cooling purposes. In the case of high-rise structures, the dense urban blocks are more likely to obstruct wind flow compared to open space where there is less obstruction. In the existence of landscape, the microclimate of a high-rise structure can be modified through radiation control where plants can be used to filter solar radiation and provide shade that helps to reduce ambient temperature and surface temperature. The plants' contributions towards improving thermal comfort can be applied in many areas such as the green roof, balcony, sky court and bio facade.

9.3 How Does Plants Improve Thermal Comfort?

Radiation is one of the thermal comfort components that can be modified using plants as the plants absorb solar radiation. However, different plants have different abilities to filter solar radiation depending on several factors. The amount of radiation absorbed depends on the density of the plant canopies and varies across species. Variation in cooling effects from different types of plants with the different physical properties needs to be identified in order to understand the absolute cooling effect to the environment. A single layer of leaf will generally absorb 80 % of incoming visible radiation, with only 10 % radiation reflected and 10 % transmitted [4]. Approximately 20 % of infrared is absorbed, with 50 % reflected and 30 % transmitted. Accordingly, the percentage of these two types of radiation that can be absorbed by a single layer of leaf is, approximately 50 %, reflected 30 %, while only 20 % transmitted. In addition, it was found that most trees can filter approximately 80–90 % depending on the leaf density, leaf arrangement and type of leaf [5].

9.4 Plant Types

In general, plants can be categorized into trees, palms, shrubs and ground covers. Trees can also be classified according to its canopy densities (dense, intermediate and open). Dense canopy is defined as trees with close arrangement and multiple stacking of foliage within the canopy. The intermediate canopy is classified between "dense" and "open" canopies. On the other hand, the open canopy has sparse foliage arrangement or spreading canopy with little stacking. Many factors must be considered when planting trees in a specific location particularly in a high-rise condition. Small- to medium-sized trees are commonly used for rooftop gardens. It is best to avoid selecting trees that produce big fruits as it may pose a safety hazard especially on high-rise rooftop garden.

Palms are categorized by its key growth form, namely whether it has single stem (solitary stem) or multiple stem (cluster palm). It was found that plants with multi-stemmed such as *Rhaphis excelsea* (Fig. 9.1) are suitable to be planted in high-rise building [6]. The multi-stemmed plant offers multiple layers of shading and radiation filtered, therefore improving the thermal comfort of the area.

On the other hand, palms with broad leaves such as *Licuala grandis* were found not suitable in fully exposed strong wind areas such as rooftop gardens (Fig. 9.2). Although it gives good performance on filtering radiation, its wide and broad leaves could not withstand the windy conditions of such spaces. However, the same species on the balcony area showed a better survival when it is planted on a planter box of semi-covered space of the same building (Fig. 9.3).

The effectiveness of plants in cooling such as shrub can be categorized by its foliage density. This is ranked from dense, mid-dense, sparse and very sparse.

Fig. 9.1 The use of *Rhaphis excelsea* in sky court garden of a high-rise building

Shrubs are used to complement the multiple layers of planting (composition of trees, shrubs and ground covers), by providing additional leaves densities. This is partly crucial as shrubs absorb the solar heat gained on ground surfaces (about 1 m height) and creates cooling effects especially when wind passed through the planted areas.

Ground cover is important in designing a landscape. The use of ground covers compared to other materials such as concrete surfaces reduces heat transmitted to the ground, resulting in the reduction of air temperature. Usage of "cool materials" presents a high reflectivity to the solar radiation, increases spectral emissivity, and therefore contributes to the increase of urban albedo [7]. The albedo is the ratio of the amount of light reflected from a material or also described as absorption of solar radiation. The trend of incorporating landscape on high-rise building today explores the use of ground covers on the rooftop such as green roof. However, most plants could barely survive on the building's rooftop especially in hot climate where plants suffer from the stressful environment with extremely high temperature and quick drought due to sunshine and strong wind. Theoretically, it is best to use native plants as they have adapted well in the local conditions, while the performance of the non-native plants may vary according to the sites and climatic changes. In North America, there were cases reported on the overuse of non-native *Sedums* that led to insect infestation, diseases, mould and fungus. A study emphasized that locally occurring native species that have evolved for many years will survive on the stress of the local climate and weather [8]. It is a common scenario to observe that there are even native species that have evolved to germinate and grow on buildings without any substrate at all in Malaysia.

Fig. 9.2 The use of *Licuala grandis* with wide and broad leaves may not be suitable in an open rooftop space

Fig. 9.3 *Licuala grandis* in a planter box of a semi-covered balcony area

9.5 Factors Affecting the Effectiveness of Plants in Cooling the Environment

9.5.1 Characteristics of Plants

The plant's characteristics affect the shading and its potential in modifying the microclimate. The canopy form and tree structure are influenced by branching and twigs, and leaf cover. These two factors may affect the overall character of tree shape and density, which varies between species. Based on the radiation interception concept through flat leaves trees' canopies, leaf area index (LAI) is defined as a dimensionless value of the total upper leaves area of a tree divided by the tree planting ground area. By definition, 100 % of direct solar radiation interception means that canopy shadow should equal ground planting area. Thus, LAI for the same tree could vary from a season to another by deciduousness, from age to another by growth. It was proven that light is reduced by up to 95 % in areas of shade caused by higher branching density, mostly in shaded areas or close to tree trunks [9]. This is termed as the transmissivity value of a plant. Transmissivity value allows the identification of trees with a heavy or light shade that is influenced by branching and leaf cover. The light transmitted underneath the canopy after absorption and reflection from the tree influenced the intensity of the shade and glare.

A study concluded that optimization between ground surface physical properties and the amount of heat trapped by a tree could help in increasing the LAI value [10]. Differences in LAI measured in tree canopy density and percentage of light transmission were found to contribute to a significant radiation filtration underneath the canopies. The higher LAI values and lower transmissivity percentage value correspond to the higher number of radiation filtered. This implies that LAI values greater than five can approximately filter more than 90 % of radiation, while LAI value less than five filters about 70–90 %. Further study found the impacts of trees at ground level, in particular those with larger LAI value to be significant [11]. Trees with high density (LAI = 6.1) produced only 7 % radiant heat underneath the canopy, while trees with low density (mean LAI = 1.5) produced 21 % of radiant heat. Thus, a higher density tree canopy that produces a low amount of radiant heat will result in the lowest amount of terrestrial radiation underneath the canopy. This condition will promote evapotranspiration, and the production of more latent heat helps decrease the surrounding air temperature and increase relative humidity. Trees with high foliage density and multiple layers of branching are recommended to maximize the radiation interception and greatly modify the thermal heat underneath the canopy and surrounding area. In fact, the amount of trees may correlate with further improvement in microclimate. By calculating LAI, plant canopies across tree species, and across trees within a species, can be compared and evaluated. It is the key measure used to understand and compare plant canopies. Therefore, both LAI and transmissivity values are important to understand the relationship between both values and radiation filtration. In addition, incoming radiation filtration is well correlated with LAI values, and these evaluation methods can be used in determining the density of a tree canopy.

The previous study conducted in Suntech building, Penang, a 21-storey high-rise office building, showed the effectiveness of different species of ornamental plants according to its LAI and how it influences the radiation filtered (%) and light transmitted through the plants [6]. The plants were located at three distinctive landscape gardens (Table 9.1).

9.5.2 *Shading Effects*

Another way of radiation control is through shading. On average, tree shading contributes to about 80 % of the cooling effect in hot and humid climate region. In a study of outdoor behaviour, 93 % of people visiting a public square in summer in Taiwan chose to stay under shaded trees or in building shade, demonstrating the importance of shade in outdoor environments [12]. Each plant casts its own distinctive shadows both in shape and density. The shade casts by trees is dependent on the types of foliage, which will determine how dense or sparse the shade density is. In daytime, shade trees indirectly reduce heat gain in buildings by altering terrestrial radiation and eventually reduce ground surface temperature [7]. It was recommended that there are three major factors to be considered to optimize the cooling effect in urban environment at street level [11]. These include high tree canopy density with LAI of 9.7, larger tree quantities and installation of cool materials with albedo value of 0.8. These combinations of modifications help to improve the outdoor air temperature when designing urban outdoor landscape and indirectly contribute towards building energy performance particularly in the tropical climate condition.

Table 9.1 Overall summary of transmissivity, leaf area index (LAI) and radiation filtered under each plant species in three different landscape gardens of a high-rise building

Location	Species	Mean of the plant sample		
		Transmissivity	Leaf area index (LAI)	Radiation filtered (%)
Sky court garden	*Rhaphis excelsea*	2.43	2.98	90.17
	Bamboo grasilis	9.37	2.68	78.46
	Rhaphis humilis	7.99	3.70	61.28
	Dwarf schefflera sp.	14.99	2.19	56.10
Balcony garden	*Licuala grandis*	12.94	4.80	59.30
	Ptychosperma macarthurii	8.86	2.78	83.10
Rooftop garden	*Eugenia oleina*	14.52	1.79	77.08
	Licuala grandis	16.62	3.69	75.40
	Bucida molineti	26.20	0.86	64.58

9.5.3 *Plants with Multiple Layers (Combination of Layers of Leaves and Three Canopy Layers)*

More layers of leaves will result in better efficiency at reducing solar radiation underneath a tree canopy. This is further studied by [5], who introduced the three-layer canopy structures that consists of tree canopy, shrub layer and field layer that depicts the rainforest canopy layer. The purposes are to create a high-quality shaded area, encourage high relative humidity level, offer an optimum evaporative comfort cooling and lower the overall temperature of surrounding urban areas. The upper layer involves tall trees with loose density (LAI < 5) and broad spreading form characters as to allow radiation to be partly filtered before the next layer of leaves. In the middle layer, higher density trees (LAI > 5, transmissivity <10 %) are recommended. A source of light is required for photosynthesis process here. Species that are round or solid oval form that have multiple layers and broad leaf characters are favourable for better absorption and radiation filtration. This ambient will create better moisture retention and reduce evaporation of soil water at ground surface. As for the field layer, full-shaded green plants (e.g. thick low shrubs or turf) are recommended. This is to promote more evaporative cooling and transpiration process, stabilize the temperature and absorb excessive thermal heat underneath the canopy.

Besides multiple layers of foliage cover, the arrangement of leaves would help in forming the canopy structure and the variation of density in a tree canopy. Leaf and bud arrangement may significantly contribute to the pattern of growth and form of individual branches and the overall appearance of tree crown [13]. In addition to this, the maturity and height of the tree will also influence the density of the canopy [14]. The use of *Bucida molineti* is well known for landscape today, especially on parking spaces (Fig. 9.4). This is particularly for the matured species as it has a unique form of horizontal spreading of branches that allows shading. The human thermal comfort and energy budget will also be improved when trees are planted in clusters. This is due to the larger reduction in air temperature and ground surface temperature, hence creating shaded areas.

9.6 Applications of Green Elements

9.6.1 *Balcony*

In a smaller scale development, planting can be incorporated with balcony design. Balcony is the simplest form of transitional space that can be incorporated with greenery. Balcony is described as a platform that is built on the upstairs outside wall of a building, with a wall or rail around it. A good design of a balcony generates wind pressure that contributes positively towards indoor airflow. Size of openings at the balcony is important in order to achieve an appropriate indoor wind speed.

Fig. 9.4 *Bucida molineti*, a popular species for landscape use today as it has wide-spreading branches that allow more shading and small leaves that allow easy maintenance

This will benefit individuals in high-rise dwellings and small commercial units. However, the limited space only allows plants with appropriate height and size. Hence, the choice of suitable plants is crucial for its survival. Plants can be planted in planter box, potted, or even grows vertically as a screen such as creepers (Fig. 9.5).

9.6.2 Sky Court

Sky court is a recessed balcony area with full-height glazed doors from the internal areas that open out to the terrace spaces [15]. Sky court is used to serve as transitional zones between the inside and outside areas to receive direct flow of external wind and redirect it into the indoor environment. It is one of the best areas for planting as it has opening to the outdoor environment. These spaces need not be totally covered from above, but sometimes, they are shielded by a “louvered roof” to encourage natural ventilation in a building. Sky court, a popular term in the bioclimatic architecture movement, was introduced by Architect Ken Yeang. He defined sky court as a “large terraced area that can be both private and communal and is located in the upper parts of a tall building”. Sky court features could

Fig. 9.5 The use of palm species is suitable for balcony with double volume as it helps to shade the area effectively

effectively act as private communal spaces, wind-controlled zone, and sun-receiving spaces [16]. This will benefit the occupants' satisfaction with incorporation of natural ventilation and green landscape. The large space that allows natural ventilation and daylighting is good for planting. More types of plants such as trees, palm and shrubs can be incorporated in this area (Fig. 9.6).

9.6.3 Building Envelope/Vertical Planting

Biofacade is becoming a trend in the development of high-rise structures particularly in the urban cities. The shortage of land increases the demand of high-rise properties; hence, landscape evolved from gardens and parks to vertical planting. Biofacade has been developed as vines on wall, bioshader, green wall, green façades, vertical garden, living wall and vertical greenery. Biofacade is one of the ways forward in accommodating the shortage of land due to the rapid urbanization and overpopulations in the cities. Developing cities are often densely built and have inadequate space at the ground level for the growing of trees. In high-rise buildings, available space for greening is usually focused on rooftops and outside wall of

Fig. 9.6 The spacious area of a sky court allows for more planting to be incorporated in high-rise development

building. The biofacade can be served to supply the ecological and psychological needs of the population, especially for the urban high-rise dwellers. Other than addressing the climate issues, biofacade acts as an agriculture medium for food security. Achieving self-sufficiency through agriculture reduces high dependency on food importation to the country. Since Malaysia is heavily dependent on importation of food items, the expected emerging issues in the future would be the increase in food price. Therefore, growing a biofacade will help in supplying the basic needs such as fruits and vegetation to individual household. These trends have been explored in most developing countries to cater for its shortage of land due to rapid urbanization such as in Singapore, China and Japan.

9.6.4 Green Roof

Installing a green roof is one good example of green approach in high-rise buildings. One needs to understand the usage and functions of the green roof before constructing a green roof. Green roof is a vegetated system where plants are planted on the roof using a growing medium lay on certain layers of the system. Constructing simple green roof and rich landscape gardens with trees or ornamental plantings requires different needs. There are two main classifications of green roof, which is intensive and extensive. Intensive green roofs, also known as roof gardens, use a planting ground with thick soil and deeper substrate to allow deeper rooting plants such as shrubs and trees to grow. This involves a greater load of more than 150 kg/m3 with 100 mm of substrate and a higher amount of organic material than extensive systems [17]. They are normally accessible as a recreation space for occupants and often incorporate landscape such as paving, seating, children's playgrounds and other architectural features. An extensive green roof uses a planting ground with shallow and light substrates without significant structural alteration to the building. It is less expensive, requires lower maintenance and allows only limited accessibility compared to intensive green roof. They are distinguished by being low cost, lightweight (50 kg–150 kg/m3) and with thin mineral substrates of up to 100 mm. Only limited plant species can grow in the shallow soil or substrate layer with low holding capacity, typically sedum or lawn.

9.7 The Prospects of Greenery in Future Building Development

Plants have a great potential in improving the microclimate of transitional spaces and can be introduced as green roofs, vertical plantings and landscape gardens. Aesthetically, greenery plays a role in beautifying buildings and adds value to the project. The use of green elements can be explored to minimize the energy used to cool down buildings. Plants are considered as an alternative feature that can be manipulated to lower outdoor temperature in high-density environment. The trend of incorporating plants in high-rise buildings today has been recognized by some developers as a key selling point to promote sustainable living. The previous research has shown that green roofs have many economic, environmental and social benefits. Economic benefits include increasing the marketability of the building properties in branding it as a green building. The awareness towards sustainability living and quality of life increased the demand of green building concept. Environmentally, research on the effective of green roof and sustainable issues has been recurrently discussed today. Estimation study of energy saving for rooftop gardens in Singapore showed that green roof results in a reduction of 1–15 % of annual energy consumption [18]. The effects of planting can be seen distinctly when observed on surface temperature. On the other hand, green approach improves psychological well-being. Hence, existence of transitional spaces with greenery such as green roof and landscape brings the building occupants together. This is crucial in high-rise development where the exposure to nature is limited.

In line with the green roof development, the Green Plot Ratio (GnPR) was introduced in Singapore [19]. The innovative concept for measuring greenery is set to be used as an "architectural and planning metric" for greenery in cities and buildings [19]. GnPR was defined as the "average LAI of the greenery of a site", where the LAI of a plant is its one-sided leaf area per unit ground area of the plant canopies. In nature, the GnPR is a three-dimensional metric where it involves measurement of green volume where most metrics make either one- or two-dimensional measurement of greenery. The one-dimensional metric is a measurement of population numbers, which involves inventory of plants. The two-dimensional metric is a measurement of green area, and the metrics involve vegetation canopy cover, green buffer area, green area and Seattle Green Factor Biotape Area Factor. GnPR helps to determine the appropriate green ratio and stipulates the green density that should be plotted to the site [20]. The City Square Tower Area (Precinct Central) in Malaysia was calculated to contribute 0.4 GnPR, which accumulated to 7 % of the existing greenery in the area and contributed to the average of 30–32 °C in a hot sunny day.

9.8 Conclusion

Plants benefit the environment in many ways. The exploration of growing plants in buildings is one of the approaches to reduce the rapid development of concrete jungle in the cities. Loss of greenery has resulted in global issues such as the UHI effects and global warming. The idea of incorporating the green design such as the green roof, landscape gardens and biofacade helps to cater the needs of building tall buildings with environmental consideration. The incorporation of greenery in high-rise building helps in cooling the building, allowing food self-sufficiency and improves the psychological needs of high-rise dwellers that have been separated from the nature. The ideas of planting have evolved and create a responsive ecosystem after a period of time. This responsive ecosystem is vital in ensuring sustainability of the future development.

> Land is basically two-dimensional. Trees add the third dimension of height. Evergreenness adds that quality of timelessness, which contributes a fourth dimension.
>
> Dr Francis S. P. Ng

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Chapter 10
Turbine Ventilator as Low Carbon Technology

Yih Chia Tan, Mazran Ismail and Mardiana Idayu Ahmad

Abstract There is a growing awareness among the general public, energy developers, and governments worldwide to look for renewable and alternative energy systems that capable of reducing the amount of carbon emissions. In response to the scenario, the last century has seen tremendous progress in technological development of low carbon technologies and green energy resources for building applications. The deployment of these technologies not only contributes to a significant percentage of carbon dioxide emission reduction, but also aids to reduce energy consumption and mitigate environmental impact. The need for such eco-friendly technologies in buildings has underpinned significant increases in the application of wind-driven ventilation techniques. This includes turbine ventilator, a wind-driven ventilation device or air extractor that is commonly used in attic, rooftop spaces or loft to facilitate ventilation, control high energy consumption, and improve indoor environment. In order to gain a deeper understanding into existing knowledge in this field, this paper discusses low carbon technology concept and characteristics of turbine ventilator. Furthermore, physical and operating parameters that influence its performance are also discussed.

Keywords Low carbon technology · Turbine ventilator · Energy · Physical and operating parameters

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10.1 Introduction

Energy conservation is now becoming as a hot research topic in recent years. People become increasingly aware that human in the future might face environmental crisis such as global warming, climate change, and depletion of energy resources which further lead to adverse impact such as species extinction, gene mutation, or spreading of new virus and diseases, and thus, they cannot be simply neglected. As such, low carbon technologies and green energy resources are needed to avoid these issues getting worse. In response to this scenario, various technical strategies are adopted for energy conservation in buildings through low carbon technologies, and they play a vital role in the move toward a green energy.

"Low carbon technology" is a term given to technologies that have a minimal output of greenhouse gas emissions into the environmental biosphere, but specifically referring to carbon dioxide. It means such technologies have the potential to reduce the carbon intensity of processes at every stage of the energy supply chain to end user efficiency [1]. In this concept, it takes into account the energy efficiency of a system in terms of ratio between the energy input and the useful energy output considering the form of primary energy source such as fossil fuels. Thus, low carbon technologies include lower energy technologies developed from renewable and alternative energy sources such as wind, water, solar photovoltaic, and passive solutions. By using this kind of technologies, building energy consumption can be reduced up to 20–30 % [2]. One of the main low carbon technologies used in building services is turbine ventilator, a wind-driven ventilation device or air extractor that is commonly used in attic, rooftop spaces, or loft to facilitate ventilation, control high energy consumption, and improve indoor environment. This device is well established with the advantages of cost-saving and low carbon emissions.

Turbine ventilator is invented with the purpose to extract hot air of the attic space. It is placed on rooftop, connected to attic space under the roof in order to extract the hot and humid air trapped in the attic space, in turn, to reduce the energy transfer between the attic and living spaces [3]. During hot days, heat trapped in the attic space might cause attic temperature risen up to 60 °C even with the outdoor temperature in just 32 °C [4], as a result occupant switches on air cooling electrical appliances indoor and more carbon emissions given out. Other than that, hot and moisture air trapped in attic space during hot days can also cause spoilage and breakage of roofing material, same goes in cold weather when air droplets condense in the attic space [4], in the end causing more materials wastage. Hence, air ventilation in attic space is very important as it can achieve thermal comfort inside a building, avoid harmful effects to the human's health, and help lowering carbon footprint.

The invention initiated by Meadows [5] over 80 years ago was called "rotary ventilator" at first and has now developed into many kinds of design. The application makes use of natural wind energy as the active force to rotate the turbine is considered energy recovering and recycling, making turbine ventilator a good sustainable energy model and very environmental friendly [6, 7]. Another major purpose of this application is also to enhance the indoor air quality, while good ventilation is a key element of maintaining good health of an occupant in the building [8]. Therefore, scientists believe the advantages of using this application is significant [9–11].

10.2 Mechanism and Concept

Turbine ventilator is a wind-driven technology which uses natural outdoor wind to help the rotation of the turbine. The ventilation strategy of turbine ventilator is said to be both active and passive [12]. In common, the mechanism of turbine ventilator is explained as follows: When the outdoor wind blows passing through or by the turbine ventilator, the wind becomes a driving force that pushes the turbine and causing the turbine to rotate, and thus, it creates a centrifugal force inside the duct, and hot air gets extracted. When there is no wind blow or stagnant air at the outdoor, the mechanism will become a passive strategy, due to the existence of net free vent area at the vertical blades which can then induce the stack effect and extract hot and stale air out from the building if there is a sufficient temperature differential between outdoor and indoor [13].

A simple mechanism of turbine ventilator has the benefits of almost negligible electricity usage, no doubt corresponding to market demand of cost-saving and low carbon emission application. However, the efficiency of conventional type turbine ventilator in terms of air extraction was found to be not very recognizable during low outdoor wind condition [14]. In order to enhance its performance and efficiency of air extraction, some turbine ventilators are designed and developed as hybrid technologies, in which electrical fan is installed near the opening of the turbine's bottom and the duct. Then, the electrical fan will be connected to a photovoltaic system that it can make use of solar energy as the power resource [15, 16].

Another hybrid turbine ventilator has then further modified by Nordin et al. [17] in order to obtain more thermal comfort in the building, by attaching an air propeller onto the top of hybrid turbine ventilator to help rotation of the turbine ventilator and the inner fan. The modification succeeded to enhance the rotational speed, and the thermal comfort is well achieved too. Both conventional and hybrid turbine ventilators have the pros and cons in between regarding their performances. As such, parameters of performance testing are further discussed as they are important in investigating the feasibility of different types of turbine ventilators.

10.3 Performance Parameters of Turbine Ventilator

In general, performance of turbine ventilator is influenced by two major parameters, which are operating and physical parameters. The operating parameters include outdoor wind speed, induced air flow, ventilation rate, rotational speed, and air temperature. On the other hand, the physical parameters are size (diameter), duct size, height, blade design, and number of blades. This section discusses both parameters.

10.3.1 Operating Parameters

10.3.1.1 Ventilation Rate, Induced Air Flow, and Aerodynamic Force

Ventilation rate reflects effectiveness of the turbine ventilator as higher ventilation rate indicated good air extraction outward the building. Ventilation rate in many literature is discussed in terms of different units, i.e., l/s, m^3/s, air change per hour (ACH), and CMH (induced ventilation rate) [3, 11, 12, 14–16]. Lai [14] ran a series of experiments on ventilation rate in buildings with and without turbine ventilator, showing that the installation is helpful to induce airflow in the buildings.

On the other hand, a simulation of airflow computational fluid dynamic (CFD) technique code (FLUENT) was performed by Farahani et al. [18] to visualize the air flow behavior around and within a rotating turbine ventilator. Aerodynamic force and air flow pattern were shown in the study, which can be further investigated in the performance testing of turbine ventilator. Later, Shieh et al. [16] and Lien and Ahmed [19] performed CFD technique in their studies. Shieh et al. [16] found that hybrid turbine ventilator provides approximately four times the exhaust capacity of a conventional ventilator, while air velocity is always stronger closer to the middle of the space no matter in which mode due to upward flow that forms in the middle and is joined by the air from the openings on both walls. On the other hand, Lien and Ahmed [19] concluded that CFD validation offered further scope to investigate both internal and external flows around and within a rotating ventilator and CFD analysis could be used as a cost-effective aid to future design and development of rooftop turbine ventilators with enhanced performance CFD technique.

10.3.1.2 Air Temperature Reduction

As the main purpose of the invention is to extract hot air, reduction in air temperature is therefore needed to be observed. Lien and Ahmed [19] have evaluated wind-driven ventilator for enhanced indoor air quality and carried out a numerical analysis. They investigated several factors including room temperature and found that mean temperature reduced from 27.71 to 27.26 °C as the ventilator exhaust rate increased from 1 to 3 m/s [20]. Meanwhile, a comparative study was made by Ismail and Abdul Rahman [21] to investigate effects of different hybrid turbine ventilators onto indoor thermal comfort. Results showed that it was obvious to see reduction in temperature with hybrid turbine ventilator (HTV), and they concluded that reduction of air temperature was more influenced by air change hour (ACH) and ventilation rate.

10.3.1.3 Outdoor Wind Speed and Outdoor Weather

Outdoor wind speed and weather can be a constraint to the effectiveness of turbine ventilator as discussed in [14]: When there is no air velocity occurs, the air flow is blocked at the connecting duct. In most experiments, the ventilation rate is directly proportional to the outdoor wind speed. In Lai's experiment, he controlled the wind speed from 10 to 30 m/s. However, Dale and Ackerman [3] observed that the flow rate of a turbine ventilator under field conditions was dependent on the wind speed and wind direction. Since there is various climate and weather conditions in different countries, it is recommended the performance testing of turbine ventilator is set with suitable range of outdoor wind speed which depends on a country's climate in order to test its feasibility.

10.3.1.4 Rotational Speed

In performance testing, some scientists investigate rotational speed of the turbine ventilator instead of ventilation rate. Lien and Ahmed [22] ran an experiment to investigate how roof inclination angle affect the rotational speed. It was found that the forces performing on the ventilator and its rotational speed were found to have a linear increasing trend with the free-stream velocity, which means that the rotational speed of turbine decreased with the increasing of the inclination angle of the roof. Besides, Khan et al. [11] also tested the performance of turbine in terms of rotational speed, by comparing different throat diameter, blade design and construction materials of turbine ventilators, and the results showed a significant impact of these factors onto rotational speed.

10.3.2 Physical Parameters

Physical parameters of turbine ventilators usually depend on the configuration of turbine ventilator itself. Modification of turbine ventilator can then be made to achieve higher performance by investigating operating parameters as follows.

10.3.2.1 Size (Diameter), Duct Size, and Height

Experiments comparing performance of turbine ventilator in different sizes and heights were carried out by Khan et al. [11], Lai [14], Revel and Huynh [10], and West [23]. West [23] concluded that 50 % increase in blade height gave a 13.5 %

increase in air exhaust rate and added that the increase in height had an advantage on inclined roof houses, allowing more blade area to be exposed above the roof ridge line, assisting extraction to be occurred.

Lai [114] compared three sizes of turbine ventilators, i.e., 6, 14, and 20 inch in diameter in his experiments. He found that as expected, a bigger size of turbine ventilator showed a better ventilation rate; however, the performance of 14-inch and 20-inch turbine ventilator was almost the same. People tend to install the 20-inch turbine ventilator with a belief that it has better effects. Khan et al. [11] too support with evidence that larger ventilators have significantly greater ventilation rates as they have larger vane diameters, yet believe that good ventilation rate is as well caused by the blade design and construction materials of turbines. Besides, Revel and Huynh [10] investigated on different types of turbine and concluded that larger throat or duct size can result in better ventilation rate.

10.3.2.2 Blade Design and Number of Blades

Khan et al. [11], in their study, compared the blade designs of turbine ventilator in curved and straight blades, and the findings showed that curved blade ventilator had about 25 % larger flow rate than a straight blade ventilator, and added that the construction materials with lighter weight could enhance the ventilation further. Lien and Ahmed [19] stated that by increasing 50 and 100 % of ventilator blade height, the improvements of between 15 and 25 % in exhaust mass flow rate were achieved, respectively. Number of blades of turbine ventilator is not much discussed in the literature; however, its configuration is commonly directly proportional to the size; hence, ventilation rate increases when the number of blades increases [24, 25].

10.3.2.3 Roof Inclination Angle and Roof Shape

Apart from the configuration of turbine ventilator itself, the positioning and the placement of turbine on the rooftop are fairly important. Lien and Ahmed [22] conducted an experiment regarding effect of roof inclination angle and found that the rotational speed of turbine ventilator was harder to achieve with more inclined roof, as stronger wind was needed to move the turbine. Meanwhile, Abohela et al. [26] discussed the effect of roof shape onto the wind direction and rotational speed of turbine, and stated that the best location for mounting a wind turbine on top of the investigated roof shapes when the wind was gusting parallel to the roof, where different roof shapes were found with different advantages associated with the building height.

10.4 Conclusion

This paper discusses mechanism and concept of turbine ventilator as a low carbon emission technology, and how it plays a role using wind energy to achieve its sustainability. The mechanism and concept are presented by taking into account the conventional and hybrid design of turbine ventilator. On top of that, operating and physical parameters are presented by reviewing previous works as to show how these factors can influence a turbine ventilator's performance.

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Chapter 11
Green Binderless Board from Oil Palm Biomass

Rokiah Hashim, Wan Noor Aidawati Wan Nadhari and Othman Sulaiman

Abstract Wood is globally desirable natural material used for home, construction, furniture, building, tools, vehicles, indoor and outdoor application, and decorative uses. Thus, there is a need for alternative material by manufacturing composite panels. In the economic activity of wood-based industry, particleboards are widely used due to its performance and cost efficiency. Using material that demonstrates positive environmental qualities is also a main area of consideration. However, due to the environmental concern, research and engineering interest have been changed from using synthetic adhesive to a new biobased adhesive or self-bonding board that is free from synthetic adhesive called binderless board. The search for alternative, potential, and sustainable raw material has been distributed over a large area around the world. This chapter considers the area of binderless board manufacturing, treatment, and other processes using oil palm biomass as raw materials. The mechanical and physical properties are viewed and compared with other binderless boards made from other types of oil palm biomass. The results presented here are only based on the environmental aspects without coinciding any economic factors or costing.

Keywords Binderless · Green composite · Natural adhesive · Oil palm biomass

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11.1 Introduction

In these days, the idea of using the green material to take place with wood as a raw material has become more major concern. The society is becoming aware of the potential environmental benefits of this preference to conventional production. More researches on green materials have been published regarding the manufacture of binderless board in reducing buildings' energy, as for the environmental concerns and for reducing negative human health effect purpose [1–6]. However, choosing material that demonstrates positive environmental qualities is also a main area of consideration. Binderless board is a panel formed without using any synthetic adhesives [7–12]. It can be produced by hot pressing, and the board's self-bonding is derived from the chemical components of the board. It is so-called self-binding particleboard without using any adhesives. Binderless board is less hazardous, biodegradable, and environmental friendly certainly in terms of waste disposal and recycling. Binderless board has no formaldehyde emission and has no dependency on the petroleum-based chemicals such as resin. Additionally, resins are expensive and involve high cost in particleboard manufacturing. Reducing or eliminating the use of resins will lower the cost of the manufactured and be available at economical value and become a suitable panel to the biosphere [4, 13].

Binderless board is possibly made from variety of lignocellulosic material including the oil palm biomass. Malaysia is known as one of the largest palm oil producers in the world. As a biomass potential, 30 million tonnes of biomass can be mobilized in 2020 at competitive costs. Besides palm oil, oil palm plantations produce abundance of biomass such as empty fruit bunch (EFB), kernel shells, mesocarp fibers, fronds, and trunks [14, 15]. Oil palm trunk is generated only in particular time, when oil palm trees are felled at plantations. These types of biomass were simply burned or left in the plantation and not fully make practical and effective use of them. Oil palm biomass includes oil palm frond, oil palm trunk, oil palm leaves, empty fruit bunches, and others [15]. Large amount of oil palm biomass, environmental issue, shortage supply of wood, cost, and formaldehyde issue could be a reason to produce all types of green binderless boards from oil palm biomass and possible for further development. This will lead to the involvement in the economic sector and the development of the available renewable waste resources obtained during replantation of oil palm tree. Malaysia could be financially well-being by adding value to waste, decreasing the problem of environmental risk due to landfill and burning of oil palm trunk in the field during replantation, providing a better low-cost panel which exhibits a comparable quality with the existing panels in wood-based industry, and improving quality life of the community. It is also a road chart of innovation agency in line with government effort.

Binderless boards could fit perfectly in a biorefinery concept for total integration utilization of oil palm biomass. A biorefinery is an integrated facility for efficient coproduction of materials, chemicals, transportation fuels, green gases, power, and/or heat from biomass [16]. Malaysia is rich in oil palm biomass which is an undepletable carbohydrate-based raw material available. Oil palm biomass is one of the renewable sources of carbon-based fuels and chemicals. A large range of biorefinery products based on biomass and binderless boards can be placed under composite materials. Biological raw materials from renewable resources are classified as foods, feeds, pharmaceuticals, and biobased products. The biobased products include biomaterials, fuels, energy, and biochemicals. The composites materials are as part of biomaterials [17].

11.2 Historical Development

The point in time of binderless boards was started long time ago since 1928 [7, 18–20]. Later, Howard and Sanborn [20] published what is today oldest available patent on binderless boards made from wood. It was put forward for consideration that binderless boards will become great significant products, especially in countries, which have no or less wood supplies and no satisfactory chemical industries but a lot of agricultural residues [7]. The conventional board contributes to the negative side effects such as health risks caused by the emission of volatile organic compounds from the synthetic adhesive and problems concerning issues such as waste disposal or recycling. Adhesive also is generally accepted to be the most expensive raw material for making particleboard or dry fiberboard. It consumes more than 50 % of the cost of the particleboards. The cost of this substitute is high due to use of adhesive [21]. One possible solution to these problems is to reduce or exclude the adhesive in board manufacturing. Many studies have been published concerning the production of binderless board. The material and types of binderless boards made in previous studies are shown in Table 11.1.

Table 11.1 Materials and types of binderless boards

Types of binderless board	Material	Authors
Hardboard	Wood	[19]
Fiberboard	Wood	[18]
Fiberboard	Plant material	[22]
Particleboard	Baggase	[7]
Fiberboard	Fiber furnishes	[8]
Fiberboard	Lignocellulosic materials	[9]
Particleboard	Oil palm frond	[1]
Particleboard	Softwood	[2]
Fiberboard	Oil palm frond	[21]
Particleboard	Softwood	[23]
Particleboard	Wheat straw, corn pith	[24]
Particleboard	*Miscanthus sinensis*	[25]
Fiberboard	*Misccanthus sinensis*	[26]
Fiberboard	*Miscanthus sinensis*	[27]

(continued)

Table 11.1 (continued)

Types of binderless board	Material	Authors
Particleboard	Kenaf core	[28]
Particleboard	Kenaf core	[13]
Particleboard	Soybean husk	[29]
Fiberboard	Coconut husk	[30]
Fiberboard	Coconut husk	[31]
Particleboard	Kenaf	[32]
Plywood	Kenaf core	[33]
Particleboard	Baggase	[3]
Particleboard	Kenaf core	[34]
Fiberboard	Softwood and hardwood	[35]
Fiberboard	Kenaf core	[36]
Particleboard	Kenaf core	[37]
Particleboard	Kenaf core	[38]
Particleboard	Kenaf core	[39]
Fiberboard	Baggase, bamboo	[40]
Fiberboard	Coconut husk	[41]
Particleboard	Kenaf core	[42]
Particleboard	Kenaf core	[43]
Fiberboard	Wheat straw	[44]
Fiberboard	Banana bunch	[45]
Plywood	Sugi	[46]
Particleboard	Oil palm trunk	[47]
Particleboard	Oil palm biomass	[4]
Particleboard	Oil palm trunk	[48]
Fiberboard	Plantain fiber	[49]
Particleboard	*Rhizophora*	[50]
Fiberboard	Black spruce bark	[51]
Particleboard	Oil palm biomass	[10]
Particleboard	Oil palm trunk	[52]
Particleboard	Oil palm trunk	[5]
Particleboard	Oil palm trunk	[53]
Particleboard	Oil palm trunk	[54]
Particleboard	Date palm	[55]
Particleboard	Baggase	[56]
Particleboard	Cotton stalks	[57]
Particleboard	Oil palm trunk	[58]
Fiberboard	Rubber wood	[59]
Particleboard	Oil palm trunk, *Acacia mangium*	[11]
Particleboard	Oil palm trunk	[60]
Particleboard	Oil palm trunk	[61]
Fiberboard	Bamboo	[62]

(continued)

Table 11.1 (continued)

Types of binderless board	Material	Authors
Fiberboard	*Jatropa curcas L.* seed cake	[63]
Particleboard	Oil palm trunk	[12]
Particleboard	Rice straw	[6]

11.3 Processing Technique

Binderless board can be manufactured by the hot pressing system, steam explosion process followed by hot pressing system, and steam-injection pressing. The development of binderless particleboard from oil palm biomass with different methods has been carried out by several researchers as shown in Table 11.2.

Oil palm particles and fibers from different parts and species have various mechanical, physical, and chemical properties. However, water resistance remains low and does not match the standards on industrial wood-based panels. In terms of the selecting of raw materials, the use of by-products is preferred and the existence of lignin and also the storage of other biopolymers even in small quantities are certainly contributing. Combining different materials together also could be the contributing factor. It can be observed that steam pretreatment always produces relatively stronger boards with acceptable strength compared with direct hot pressing without any treatment of the materials. Higher pressure can result in considerably higher mechanical properties and the resulting densities fall with minimum difference in values [18]. The pressing temperature and time are the most important parameters for binderless board manufacturing from lignocellulosic materials. The mechanical properties of the panels were observed to increase while water absorption and thickness swelling of binderless boards decreased with increasing pressing temperature [48]. Many factors such as materials, process, parameters, and manufacturing conditions seem to be correlated with the best method to manufacture a binderless board, which could be further studied.

11.4 Bonding and Properties of Green Binderless Board

Self-bonding in binderless boards can be achieved by physical consolidation of particles under applied heat and pressure and chemical activation reactions as illustrated in Fig. 11.1. The chemical activation reactions can be from the degradation of hemicelluloses and partial degradation of cellulose to produce simple sugars. Cross-linking of carbohydrate polymers and lignin, free sugars, carbohydrates, or saccharides in lignocellulosic materials can also be served as bonding and bulking agents. Based on the previous studies, it was shown that non-wood lignocellulosic materials were the potential raw materials for binderless boards.

Table 11.2 Different methods of binderless boards manufacturing from oil palm

Type of binderless board	Type of oil palm biomass	Pre-treatment	Target density (g/cm^3)	Moisture content (%)	Thickness (mm)	Hot press temperature (ºC)	Hot press pressure (MPa)	Reference
PB	OPF	Steam explosion at 2.0, 2.5, 3.0 MPa, (5 and 10 min)	0.7, 0.8,0.9 and 1.1	10.5	6 and 12	125 and 150	25, 30, and 40	[1]
FB	OPF	Steam explosion at 20–30 kgf/cm ^{2} steam pressure and digestion period (5–10 min)	0.7, 0.8, 0.9, 1.1, and 1.2	12	6–12	125–150 (6–10 min)	–	[21]
PB	OPT	–	0.80	8	4.8	180 (20 min)	5	[45]
PB	OPB	–	0.80	7–8	4.8	180 (20 min)	12	[4]
PB	OPT	–	0.80	7–8	4.8	160–200 (20 min)	5	[48]
PB	OPB	–	0.80	7–8	4.8	180 (20 min)	5	[10]
PB	OPT	–	0.8	7–8	4.8	180 (20 min)	5	[52]
PB	OPT	Steam temperature at 100–120 ºC (25–50 min)	0.80	7–8	4.8	180–220 (15–30 min)	12	[5]
PB	OPT	–	0.60	10	5	160–180 (15–20 min)	5, 10	[54]
PB	OPT	–	0.8	7	4.8	180 (20 min)	5	[53]
PB	OPT	Steam temperature at 130 °C for 30 min	0.8	7–8	4.8	180 (20 min)	5	[58]
PB	OPT	–	1.0	7–8	4.8	180 (20 min)	12	[11]

(continued)

Table 11.2 (continued)

Type of binderless board	Type of oil palm biomass	Pre-treatment	Target density (g/cm^3)	Moisture content (%)	Thickness (mm)	Hot press temperature (ºC)	Hot press pressure (MPa)	Reference
PB	OPT	Steam temperature at 100–130 ºC (10–50 min)	0.8	6–8	0.5	180 (20 min)	5	[60]
PB	OPT (Young)	–	0.8	7	1.0	180 (20 min)	5	[61]
PB	OPT (Old)	–	0.8	7	1.0	180 (20 min)	5	[61]
PB	OPT	–	0.8	7–8	5, 10, 15	191, 195, 196 (23, 24, 30 min)		[12]

PB Particleboard, *FB* Fiberboard, *OPF* Oil palm frond, *OPT* Oil palm trunk, *OPB* Oil palm biomass

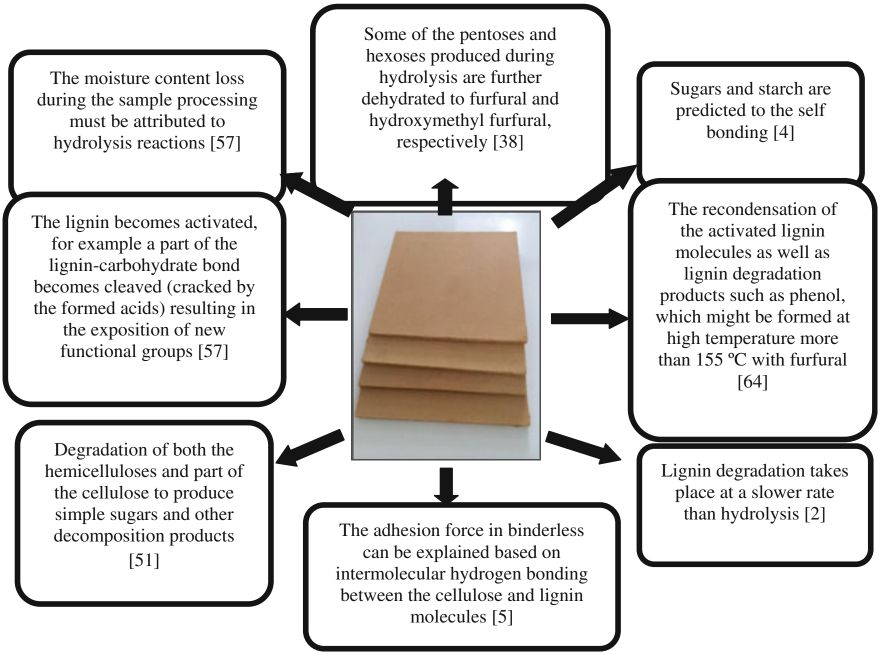

Fig. 11.1 Physical and chemical changes in binderless board

Considering that no synthetic adhesive was applied, the bonding performance of binderless boards was greatly affected by the chemical changes of materials during manufacturing process. Effects of the steam/heat treatments depend on many factors, such as pressing time, temperature, moisture content, chemical composition of the lignocellulosics, fiber or particle size, and possibly many other factors or mechanisms that are still have not been studied.

The softening temperature of lignin at moisture content of 10 % is around 115ºC [64]. Oil palm frond consists of lignin furfural, which is rich in hemicellulose, seems to be a good possibility for producing binderless boards using steam-exploded fibers of oil palm frond [21]. Particle size (between 3 and 5 cm) for oil palm strand for binderless particleboard from oil palm trunk showed a very high value of physical and mechanical properties [47]. For thermal properties, too much heat damages fibers could be the reason for the reduction in strength [48]. Effect of temperature, particle size or element type, the formation of hydrogen bonds, the formation of chemical bonds, and plasticization of the components that result from the heat during pressing or pretreatment also give an effect of the end product. Steam treatment was an effective process to enhance the bonding properties and dimensional stability of binderless boards. Hot pressing also contributed to the degradation of chemical component, to improve their binding properties (Table 11.3).

Table 11.3 Properties of binderless boards from different parts of oil palm biomass

Type of binderless board	Type of oil palm biomass	Internal bond strength (MPa)	Modulus of rupture (MPa)	Thickness swelling (%)	Water absorption (%)	Reference
PB	OPF	0.1–1.89	5–20	–	0–59	[1]
FB	OPF	0.5–1.9	0–20	6–14	15–65	[21]
PB	OPT	0.3–1.1	4–30	35–45	60–120	[47]
PB	OPB	0–0.7	1–14	20–90	65–130	[4]
PB	OPT	0.15–0.50	0.5–7.0	18–75	60–120	[48]
PB	OPB	0–0.54	1–11	20–85	65–130	[10]
PB	OPT	0.4–0.6	8–9	35–38	75–85	[52]
PB	OPT	0.54	8.18	22	51	[5]
PB	OPT	0.17–0.60	8.80–15.81	25.41–86.31	–	[54]
PB	OPT	0.4–0.9	3–7	40–50	80–110	[53]
PB	OPT	0.63	6.8	31.97	63.32	[58]
PB	OPT	0.59	22.91	17.96	42.92	[11]
PB	OPT (Fine)	0.5–1.02	4.91–8.12	38.78–59.34	72.59–100.4	[60]
PB	OPT (Strand)	0.7–1.40	20.76–25.84	32.01–44.36	58.65–72.52	[60]
PB	OPT (Young)	1.10	8.76	22.67	72.00	[61]
PB	OPT (Old)	0.65	5.25	39.60	90.70	[61]
PB	OPT	1.2–8.0	5.3–9.8	13–18	57–64	[12]

PB Particleboard, *FB* Fiberboard, *OPF* Oil palm frond, *OPT* Oil palm trunk, *OPB* Oil palm biomass

However, the mechanism of the self-bonding should be the focus of future investigation. A lot of further work is needed toward the physiochemical reactions of binderless boards to find a potential application and future development in real industrial.

11.5 Conclusion

Maintaining the concept of an environmental friendly, one approach to have an alternative green composite is binderless particleboard from oil palm biomass. Various factors could lead and contribute to the optimization manufacturing of the high performance for binderless boards from oil palm biomass such as pressing temperature, steam treatment of the raw materials, different parts of oil palm biomass, and others especially in improving physical and mechanical properties. The economical factor, improving the dimensional stability and the area of application of binderless board, should be developed for future sustainability.

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Chapter 12
Life Cycle Analysis of Building Materials

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Abstract The construction industry and building materials consume a large amount of resources and energy during its extraction, production, construction, throughout its use and even demolition process, hence causing high impacts to the natural environment. Apart from an increase in energy use, these impacts of materials range from ecological degradation, harm to human health and global warming. In order to reduce the impacts, an assessment and analysis of building materials is crucial prior to the design and construction of buildings to predict the risks and enable the decision makers to minimize those risks. This chapter gives an overview of the lifecycle approach in material selection and the assessment and analysis of materials used in the construction based on ISO 14040:2006 and ISO 14044:2006. It also presents the results of the testing on life cycle assessment of common building materials adopted in mosque construction in Iraq based on five categories: global warming, ozone depletion, human toxicity, acidification and eutrophication. This study identifies the stages in which the materials have greater impact and give recommendation in reducing the overall impact of the materials used.

Keywords Life cycle analysis · Life cycle assessments · Environmental impact · Sustainable materials

12.1 Introduction

Annually, more than three billion metric tons of raw materials are consumed to manufacture building materials and products around the world [1]. The building industry is the second largest consumer of raw materials, after the food industry [2].

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Apart from economic factors is the capacity of the human to shape the environment anywhere on the planet needs enormous environmental obligation. Buildings and associated uses are responsible for a large part of the environmental load caused by humanity [3]:

- 42 % of all energy consumption.
- 40 % of all atmospheric emissions.
- 30 % of all raw materials used.
- 25 % of water usage.
- 25 % of solid waste.
- 20 % of liquid waste.

Sustainable architecture takes into account all the aspects of the building that will affect and be affected by the environment and the users. It looks at material use and embodied energy, solar access, natural-passive heating and cooling, ventilation, water and energy use, in order to reduce its dependence on fossil fuels and non-renewable resources. In addition, sustainable architecture intends at reducing total consumption of materials and energy requirements for construction. The aim is to have as little impact on the global environment as possible without polluting either indoor or outdoor environments, while continuing to provide adequate, comfortable and safe buildings [4]. Environmental impact is defined as any change in the environment, whether adverse or beneficial, resulting from facility's activities, products or services [5].

In order to reduce the impacts, an assessment and analysis of building materials is imperative prior to the design and construction of buildings to predict the risks and enable the decision makers to minimize those risks. Life cycle analysis (LCA) is a process to enable the materials and energy flows of a system to be quantified and evaluated. Since the 1980s, the life cycle approach of materials was already advocated, whereby Becker [6] presented a flow diagram and simple formula for analysis of the consumption of critical resources and the impact by means of input/output model. More recent literature on this subject are mainly focused on energy consumption [7–9], whereas studies on the impact on environmental specification are scarce. Bribian et al. [10] concluded from their study on both energy and environmental evaluation that propagating the use of the best techniques and innovation in production plants is utmost important to replace the use of natural resources with the waste generated in different production processes and optimising the reuse and recycling of products.

12.2 Environmental Impacts of Building Materials

The environmental impact is therefore a crucial criterion for material selection. Health issues range from how materials are extracted to the effects on the manufacturing workers producing the materials and to the internal environment that results from the materials selected [11]. The impacts on the natural environment include ecological degradation due to the extraction of raw materials, pollution from manufacturing processes, transportation effects, energy inputs into materials that affects the CO_2 production and the use of refrigerants [11]. The other component of environmental impact of materials is the degree to which the material consumes energy [12]. From the extraction of raw materials to the final product, energy in various forms is embodied in the building materials generally [13]. Table 12.1 lists the environmental impacts that are related to building material manufacture, use and disposal [14–17].

12.2.1 Impact of Building Materials on Human Health

Studies show that the occupants of the building are exposed to higher levels of volatile organic compounds (VOCs) and formaldehyde in the first six to twelfth months after construction or renovation than at any other time, due to the wide range of high-emission materials (paints, adhesive, carpets, wood-based panels, furniture, and so on) used in construction [18]. Humans are exposed through numerous pathways to toxic compounds, and because the effects are not always noticeable, they are often overlooked. Some manufacturing processes can pose a risk to worker health through exposure [17].

12.2.1.1 Air Pollution

Fugitive emissions result from many activities, including production of electricity; operation of equipment used in manufacture, transport, construction and maintenance; manufacturing processes; and mining and crushing of materials [1]. Harmful chemicals can be released from the manufacturing process through discharged waste and find their way into drinking water supply [17]. Human exposure to toxic air pollutants can occur by breathing contaminated air; eating the contaminated food products such as fish from polluted waters or vegetables grown in contaminated soil; drinking water contaminated by toxic air pollutants; or touching contaminated soil, dust or water [19].

12.2.1.2 Smog

Smog is a type of air pollution and occurs when industrial and fuel emissions become trapped at ground level and are transformed after reacting with sunlight [17]. Ozone is one component of smog and occurs when volatile organic compounds VOCs reacted with oxides of nitrogen NO_x [20]. Transport of materials and equipments used at the construction site and maintenance contributes to smog producing emissions. Like air pollutants and acidification compounds, smog can have negative effects on the health of people and other biotic communities [1].

Table 12.1 The environmental impact related to building materials

Environmental impact	The relation with building materials
Impact of building materials on human health	
1. Air pollution	Fossil-fuel combustion during manufacture, transport, construction and maintenance; manufacturing processes; and mining and crushing of materials
2. Smog	Transport of materials and equipment used at the construction site and maintenance
3. Ecological toxicity	Can be encountered in all phases of the life cycle of building materials
The impact of building materials on ecological degradation	
1. Global climate change	Greenhouse gas emissions of building materials are often directly related to the embodied energy of building materials, as for most materials the emissions stem from the fossil-fuel combustion required for their production
2. Stratospheric ozone depletion	Human caused emissions of ozone-depleting substances, such as chlorofluorocarbons (CFCs; used as a propellant in manufacturing and refrigerant) and halon (used in fire suppression systems)
3. Acidification	Wind can blow these emissions from power and manufacturing plant over hundreds of miles before they deposited includes sulphur and NO_x emissions
4. Eutrophication	Manufacturing discharges, nutrients from non-point source run-off, fertilizers, waste disposal
5. Deforestation, desertification and soil erosion	Commercial forestry and agriculture, extraction, mining and manufacturing activities
6. Habitat alteration	Primary impact resulting from mining and harvesting of materials for the manufacture of building materials
7. Loss of biodiversity	Destruction of forests and habitats, and air, water and soil pollution as contributors
8. Water resource depletion	Product manufacturing activities and effluent wastes that are released into water bodies reduce water resources through pollution
Building materials impacts on energy consumption	
1. Energy consumption during the production	Energy required in manufacturing building product consumes 80 % of the total energy input in a material
2. Energy consumption during building use and demolition	Energy for transporting, on building site for construction and maintenance, and demolition
3. Fossil-fuel depletion	Used in extraction, transportation, construction and maintenance; to produce steam or heat for industrial processes; for electricity; to power machinery; and as raw material for production, materials with high-energy intensity have greater environmental impacts from fuel consumption

12.2.1.3 Ecological Toxicity

Exposure to toxic materials can cause grave damage to human health. These toxic chemicals and substances can be encountered in all phases of the life cycle of building materials [18]. Other than negative effects on human health, they can also harm animals and plants, with potential impacts on the ecosystem function and loss of biodiversity [21]. Some building materials are the source of risks to the human health at any time of their life cycle, from mining, manufacturing, construction and usage to the demolition stage. These effects are either directly through exposure to building materials or indirectly by polluting the air, food or drinking water.

12.2.2 The Impact of Building Materials on Ecological Degradation

Interaction with the environment occurs in two distinct ways, either as the source of all material resources or a sink for emissions, effluents and solid wastes. In both of these conditions, the use of materials affects the environment [1]. Overuse at sources depletes both the quantity and quality of available resources. In addition, the extraction of resources degrades ecosystems at the source location. Overuse of sinks from over-generation, and careless disposal of emissions and waste, affects the balance of natural processes and ecosystems.

12.2.2.1 Global Climate Change

Climate change has the potential to impact many aspects of life on the planet with rising sea levels, melting glaciers, recurring violent storms, loss of biodiversity, reduced food supplies and displaced populations. Global warming, a type of global climate change, is the increase in the average temperature of the earth's near-surface air and oceans. Global warming occurs when the earth is reradiated as heat and is absorbed and trapped by greenhouse effect reduces heat loss to space, resulting in warmer temperatures on earth. Three-quarter of anthropogenic greenhouse gas emission is generated from fossil-fuel combustion to power vehicle and power generating plants, and as raw material for production of synthetic polymers [22]. Other serious greenhouse gas releases result from the conversion of limestone into lime for cement manufacture, from animal agriculture, and from deforestation [1]. Greenhouse gas emissions of building materials are often directly related to the embodied energy of building materials, as for most materials, the emissions stem from the fossil-fuel combustion required for their production [23].

12.2.2.2 Stratospheric Ozone Depletion

The naturally occurring ozone layer of the stratosphere is a critical barrier prevents harmful shortwave ultraviolet radiation from reaching the earth [17]. Human caused emissions of ozone-depleting substances, such as chlorofluorocarbons (CFCs; used as a propellant in manufacturing and refrigerant) and halon (used in fire suppression systems), can cause a thinning of the ozone layer, resulting in more shortwave radiation on the earth [20]. This has a number of potentially negative consequences, such as impacts on plants and agriculture, and increases in cancer and cataracts in people [1]. Additional effects on climate and the functioning of different ecosystems may exist, although the nature of these effects is less clear.

12.2.2.3 Acidification

Acidification occurs in surface waters and soils as acidifying gases, primarily sulphur and nitrogen compounds, either by dissolving in water or adhering to solid particles. These compounds are reaching ecosystems primarily in the form of acid rain, through either a dry or wet deposition process. The primary sources of acid rain are emissions of sulphur dioxide and nitrogen oxide from fossil-fuel combustion, although they can also result from natural processes of decaying vegetation and volcanoes [24]. In material manufacture, fossil fuels are burned to produce electricity and to power equipment used in raw material extraction, manufacture, transportation, construction and maintenance. Wind can blow these emissions from power and manufacturing plant over hundreds of miles before they deposited [1]. Acid rain causes acidification of rivers, streams and oceans, lowering the PH and causing damage to fish and other animals. Soil biology is also negatively affected by acid rain with the consumption of acids by microbes and killing them [24].

12.2.2.4 Eutrophication

Eutrophication is the addition of nutrients, such as nitrogen and phosphorus, in soil or water, resulting in over-stimulation of plant growth [17]. Eutrophication is a natural process; however, it is accelerated by human activities, causing species composition alterations and reducing ecological diversity. In water, it promotes algal blooms that can cloud the water, blocking sunlight and causing underwater grasses to die. Loss of the grasses reduces habitat and food for aquatic species, sometimes causing their death [25]. As the algae die, oxygen into the water is depleted, also affecting the health of fish and aquatic species. Eutrophication impacts affect humans by affecting the taste of water (even after treatment) and by negative impacts on swimming, boating and fishing [26].

12.2.2.5 Deforestation, Desertification and Soil Erosion

Only 36 % of the world's primary forests remain as of 2005, yet forests play a key role within the health of the planet by containing half of the world's biodiversity and sequestering large quantities of carbon dioxide [27]. Deforestation, the large-scale removal of forests, contributes to negative environmental impacts such as loss of biodiversity, global warming, soil erosion and desertification. Deforestation causes soil erosion, resulting in topsoil loss and sedimentation of water bodies. In arid and semi-arid regions, removal of natural forest cover can lead to the desertification by exposing soil to wind, erosion, salinization, and biodiversity and habitats [26].

12.2.2.6 Habitat Alteration

Habitats are altered or destroyed when human activities result in a change in the species composition of plant and animal communities. This can occur through practices that change the environmental conditions and reduce habitat, as well as through differential removal or introduction of species [28]. Habitat alteration is the primary impact resulting from mining and harvesting of materials for the manufacture of building materials [1]. Habitat alteration also can occur as a result of air, water and land releases from industrial processes that changes environmental conditions, such as water quality and quantity, on naturally occurring communities [28]. Effects of habitat alteration include changes in ecosystem function and possible reduced biodiversity.

12.2.2.7 Loss of Biodiversity

Global climate change, the destruction of forests and habitats, and air, water and soil pollution have all contributed to the loss of biodiversity over the past few centuries [29]. Biodiversity was defined at the Convention on Biological Diversity, UN Earth Summit in 1992 as "the variability among living organisms from all sources, including, inter alia, terrestrial, marine, and other aquatic organisms, and the ecological complexes of which they are part: this includes diversity within species, between species and of ecosystem" [30]. Biodiversity is critical for the health of the ecosystems that provide many services keeping humans and the environment in relative balance. The biodiversity of ecosystems plays a role in regulating the chemistry of the atmosphere and water supply, recycling nutrients and providing fertile soils [29]. Biodiversity controls the spread of diseases, provides food and drugs for humans and provides resources for industrial materials such as fibre, dyes, resins, gums, adhesives, rubber and oils [17].

12.2.2.8 Water Resource Depletion

Human activities and land uses can deplete water resources, through use rates that exceed groundwater reserve and through practices that prevent aquifer recharge [31]. Product manufacturing activities use water, and effluent wastes that are released into water bodies reduce water resources through pollution. In addition, the use of impervious surfaces (such as concrete and asphalt) seriously reduces groundwater recharge, as do storm water management strategies that convey run-off away from the site [1]. Water resource depletion has serious consequences, by disrupting hydrological cycles, reducing the water available to dilute pollutants and decreasing water for human consumption and for plant and animal communities that require more abundant and constant water supplies [31].

12.2.3 Building Materials Impacts on Energy Consumption

The other aspect of building material impacts is the degree to which the material consumed energy. The industrial sector is the largest end user of energy, greater than the transportation sector or building operation [1]. Fuel type is a major factor into the equation of environmental impacts from energy use. Non-renewable fossil fuels are the primary fuel source for industrial processes, including the manufacture of building materials. At the international level, the focus is more on reducing energy consumption. Use of energy is divided between the production, distribution and use of building materials.

12.2.3.1 Energy Consumption During the Production of Building Materials

The primary energy consumption (PEC) is the energy needed to manufacture the building product which consumes about 80 % of the total energy input in a material and can be divided as shown below [32]:

- The direct energy consumption in extraction of raw materials and production processes.
- Secondary consumption during the manufacturing process. This refers to the energy consumption that is part of the machinery, heating and lighting in the factory and the maintenance of the working environment.
- Energy in transport of the necessary raw and processed materials.

12.2.3.2 Energy Consumption During Building Use and Demolition

- Energy consumption for the transport of manufactured products.
- Energy consumption on the building site. This includes consumption, which is already included within the tools used, heating and lighting, plant, electricity and machines. It also includes the energy needed to dry the building construction such as in situ concrete.
- Energy consumption during maintenance. The building needs to be maintained and renovated. Initially, one treats the surfaces by painting or impregnation materials that have energy content themselves. The next stage is the replacement of dilapidated or defective components.
- Energy consumption of dismantling or removal of materials during demolition [32].

Fossil-Fuel Depletion

The primary source of energy for materials industry is fossil fuels [33]. The direct environmental impact of building materials on energy attributes is fossil-fuel depletion. Fossil fuels are used throughout materials' life cycle to power vehicles (used in extraction, transportation, construction and maintenance); to produce steam or heat for industrial processes; for electricity; to power machinery; and as raw material for the production of plastics, other synthetic polymers (e.g. fibres) and solvents [1]. Besides the impacts associated with extraction and combustion of fossil fuels, there are no direct environmental impacts of depletion per se. Generally, materials with high-energy intensity will have greater environmental impacts from fuel consumption and related air emissions [1].

12.3 Life Cycle Approach

In order to evaluate the environmental impacts of building materials precisely, the life cycle approach has to be implemented [34]. As materials are crucial elements of buildings, knowledge of precise values of environmental impacts of building materials is essential for adequate evaluation of overall environmental impacts of building materials. Within this subject, life cycle assessment (LCA) developed an organized role for evaluating both energy and environmental performances and produced a reliable instrument for environmental selection support. Figure 12.1 shows the basic cause and effect of the life cycle processes of building materials, while Table 12.2 demonstrates the impact matrix at various stages of building materials.

According to ISO 14040 [35], the methodological framework to conduct life cycle assessment consists of four basic steps: goal and scope definition, inventory analysis, impact assessment and interpretations. The life cycle assessment (LCA) methodology

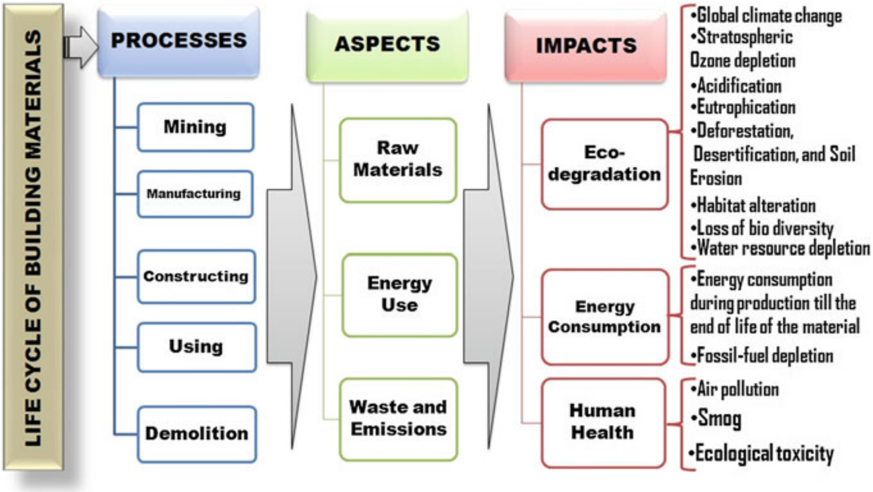

Fig. 12.1 The life cycle of building materials and their impact

is broadly implemented by the building industry, which is identified as a valuable application supporting sustainable architecture [36].

There are various applications depending on life cycle impact assessment (LCIA) available in the building industry, with different databases to support them. Life cycle impact assessment is a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle [37]. Many researchers have conducted LCIA, but the focus had been mainly on energy consumption [38–40], while this research looks at five impact factors which will be discussed in the next topic.

The most significant tools used to conduct LCA are GaBi and SimaPro [41]. Different versions of GaBi are available from educational to professional use of life cycle analysis to evaluate environmental impact, cost and social profiles of products, processes and technologies. It contains comprehensive GaBi databases with worldwide coverage as well as Ecoinvent data. GaBi application is matched by the most extensive, up-to-date life cycle inventory (LCI) database available. With more than 4500 LCI data sets depending on primary data collection from worldwide companies, associations and public bodies, GaBi databases cover most industry sectors. GaBi can handle each stage of an LCIA, from data collection and organization to presentation of results and stakeholder engagement [42].

SimaPro provides a professional tool to collect, analyse and monitor the environmental performance of products and services. SimaPro is a science-based, cost-effective tool that offers solutions for any user, with a wide range of versions to fit the different needs of business and academia. SimaPro supports LCA and EPD and comes standard with a variety of LCI databases, such as Ecoinvent v3 data, the sector-specific Agri-footprint database and ELCD. A service contract gives the full access to support and updates to software and databases. [41].

Table 12.2 The matrix of environmental impacts of the processes of building materials life cycle

Environmental impact		Material life cycle				
		Mining	Manufacturing	Constructing	Using	Demolition
Human health	Air pollution	√	√	√	√	√
	Smog	√	√	√		√
	Ecological toxicity	√	√	√	√	√
Eco-degradation	Global climate change	√	√	√		
	Stratospheric ozone depletion		√			
	Acidification		√	√	√	
	Eutrophication		√	√	√	√
	Deforestation, desertification and soil erosion	√	√	√	√	√
	Habitat alteration	√	√			
	Loss of biodiversity	√	√			√
	Water resource depletion	√	√			
Energy consumption	Energy consumption during the production of building materials	√	√			
	Energy consumption during building, use and demolition			√	√	√
	Fossil-fuel depletion	√	√	√	√	√

12.4 Methodology

The study adopted in this chapter is based on methodological standards of framework of life cycle methodology according to ISO 14044:2006 [43] and ISO 14040:2006 [35]. The study focused on global warming, ozone depletion, human toxicity, acidification and eutrophication impacts due to their most significant and relevant impacts in the region of Iraq where the research was conducted. Twelve mosque buildings in Mosul City, Iraq, were selected as a representation of Islamic Architecture with the multifunction spatial organization and symbolize the

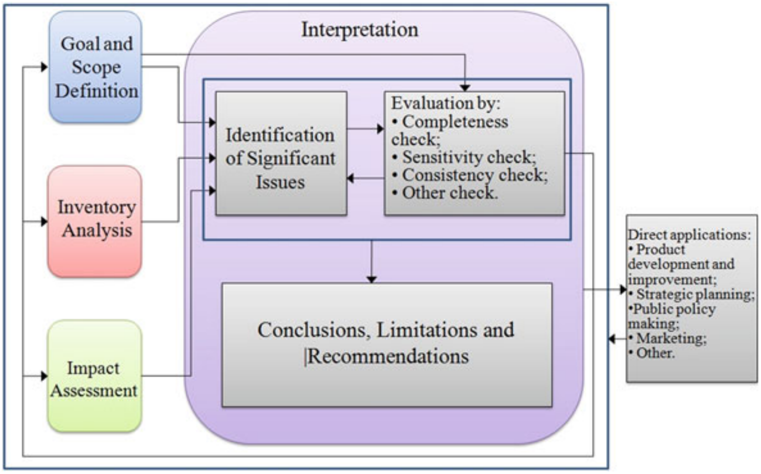

Fig. 12.2 Framework of LCA according to ISO 14040 stages

principles of spiritual hence closely associated with sustainability concept. An inventory survey was conducted on the mosques, and four main materials were identified as the major materials used in the constructing the mosques: daub stone, limestone, local marbles and clay bricks.

As shown in Fig. 12.2, the procedures to derive the life cycle assessment using environmental impact are presented within four basic steps: goal and scope definition, inventory analysis, impact assessment and interpretation.

In order to define the goal and scope of the project and then conduct an inventory analysis, data documentation form had been proposed with two main parts. The first part of the data documentation form is concerned of organization and documentation the goal and scope of the proposed project, while the second part of the form is concerned for life cycle inventory. All inputs and outputs for each process are quantified and classified then relating to unit process and functional unit in proposed table. The main task at this stage is to design the process plan of the product within the system boundary proposed earlier. There are four options in creating the process plans to define the system boundaries as follows: cradle to grave, cradle to gate, gate to grave and gate to gate [44].

All quantitative and qualitative data collected and documented in the data documentation form are converted into GaBi Education software. To get the results of impact assessments, GaBi has options to classify and characterize the environmental impact by selecting an impact assessment method. Moreover, depending on the goal and scope of the project, the impact categories can be selected. This analysing step performed by GaBi balance application based on plan of the project.

Various methods can be employed to perform a life cycle impact assessment (LCIA) such as TRACI or CML [42]. The Centre for Environmental Studies (CML) of the University of Leiden is the method focused on a series of environmental impact categories expressed in terms of emissions to the environment.

The CML method consists of classification, characterization and normalization. TRACI is the tool for the reduction and assessment of chemical and other environmental impact which developed by the US Environmental Protection Agency (EPA) [45]. The selection of impact categories depends on the goal of the study and covers the environmental effects of the analysed product system. The selected impact assessment method and impact categories must document in the goal and scope definition. After the appropriate impact categories are chosen, the LCI results are allocated to one or more impact categories. In case substances result in multiple impact categories, they should be classified as contributing factors to all related categories. After getting the environmental impact results of the product, the fourth step of the framework is ready to perform which it is an interpretation of the results.

12.5 Results

The method used in this study to structure the information is by expressing the contribution as a percent of the total "relative contribution". The feature of GaBi that used to reveal significant issues is "weak point analysis". This option interprets which process of the life cycle of any materials contributes to each environmental impact category. The other option of the weak point analysis is changing the quantity under investigation to diagnosis the effective substances or flows that contribute to each category of environmental impacts. Weak point analysis was adopted for the five categories to overcome the lack of information about the threshold of acceptable measurements and the slight impact of the relative quantities of the used materials.

12.5.1 Relative Contribution of the Processes to Environmental Impact Category

Table 12.3 interprets the relation of the processes of the life cycle of four materials under investigation to each environmental impact category. The emissions to air and to water resulted from the energy conversion process contribute to the five environmental impact categories in the four building materials. The relative contribution values presented in Table 12.3 indicate that energy conversion is the highest contributed process in the life cycle of four materials. Energy conversion needed in the extraction and manufacturing stages of the life cycle of the materials. The emissions to air resulted from transport contribute to global warming and acidification are relatively low in the life cycle of daub stone, limestone and local marble. So the emissions to air in the disposal process at the end of the life cycle of the materials are contributing to ozone depletion higher than their contribution to global warming. A transport process occurs during the life cycle of the materials

Table 12.3 Relative contribution of the effective processes that contribute to each environmental category of the four building materials

Environmental impact categories	Processes	Building materials			
		Daub stone (%)	Limestone (%)	Local marble (%)	Clay brick (%)
Global warming	Energy conversion	66	51	76.1	60.4
	Transport	21.9	25.6	13.2	
	Disposal	12.2	23.4	10.2	
	Construction industry				35.9
Ozone depletion	Energy conversion	47.3	51.5	80.2	35.1
	Disposal	52.7	48.5	19.3	57.6
Human toxicity	Energy conversion	95.2	84.6	96.5	99.7
	Disposal		11.4		
Acidification	Energy conversion	54.2	33.8	59.5	85
	Transport	36.6	37.3	24.8	
	Disposal		29	15.4	
Eutrophication	Energy conversion	92	42.3	89.6	67.2
	Disposal		57.7		12.2
	Construction industry				16.8

many times: the raw materials from mining to construction sites or to manufacturing site then to the construction site. The emissions to air resulted from the construction industry are contributing to global warming in the production of clay brick, and the emissions to water are contributing to eutrophication. Construction industry process is effective in the production of clay brick.

12.5.2 Relative Contribution of the Substances to Environmental Impact Category

Table 12.4 shows the relative contribution of the substances emitted through the life cycle of the building materials that contribute to each environmental category. Through the life cycle of daub stone, the relative contribution to global warming is 82.9 % from the total emissions of carbon dioxide combined with 13.6 % of the total emissions of methane. Nevertheless, for limestone, local marble and clay brick, the impact to global warming from carbon dioxide is 95.8 %, 91.1 %, and

Table 12.4 Relative contribution of the effective substances that contribute to each environmental impact category of the four building materials

Environmental impact categories	Substances	Building materials			
		Daub stone (%)	Limestone (%)	Local marble (%)	Clay brick (%)
Global warming	Carbon dioxide	82.9	95.8	91.1	94.7
	Methane	13.6			
Ozone depletion	R 114 (dichlorotetrafluoroethane)	99.9	99.9	99.8	99.5
Human toxicity	Formaldehyde (methanol)		12.8		
	Hexane	83.7	14	72.5	
	Xylene		55.6	11.8	84.1
Acidification	Ammonia			14.1	
	Nitrogen monoxide	35.2	34.6	23.8	51
	Nitrogen oxide	16.7	24.6	24.1	
	Sulphur dioxide	33.9	36	34.1	39.3
Eutrophication	Chemical oxygen demand		10.4		42.6
	Ammonium				16.8
	Nitrate	64.7	38.8	65.1	24.4
	Nitrogen organic bounded	17.7		13.7	
	Phosphorus		29.3		

94.7 % of the total emissions, respectively. The relative contribution to ozone depletion is totally R114 for the listed materials. The highest substances that contribute to human toxicity vary according to the material. For daub stone and local marble, hexane represents 83.7 and 72.5 % of the total emissions, respectively. While for limestone and clay brick, xylene represents 55.6 and 84.1 % of the total emissions, respectively. The substances contribute to acidification are as follows: nitrogen monoxide, 35.2 % of the total emissions for daub stone and 34.6 % for limestone, and sulphur dioxide 33.9, 36, 34.1 and 39.3 % of the total from the life cycle of daub stone, limestone and clay brick, respectively. The substances that contribute to eutrophication are as follows: chemical oxygen demand with relative contribution 42.6 % of the total emissions from life cycle of clay brick, nitrate with relative contribution 64.7, 38.8 and 65.85 % of the total emissions from life cycle of daub stone, limestone and local marble, respectively, and phosphorus with relative contribution 29.3 % of the total emissions from life cycle of limestone.

The relative contribution identifies the substances that contribute to which of the environment impact category. From the identification, alternative techniques and processes can be adopted in the life cycle of the building material to reduce the substance and its impact.

12.6 Conclusion

For clay bricks, the highest significant impact categories of the life cycle are global warming, acidification and eutrophication. The phase of life cycles for clay bricks with the highest burdens is manufacture process due to the emissions resulted from energy consumption for furnace to dry the bricks. The most crucial interventions among the inorganic emissions to air are as follows: carbon dioxide, nitrogen monoxide and sulphur dioxide, whilst the inorganic emissions to water are nitrate and ammonium. The source of these emissions has been determined during the thermal process.

For local marble, the highest important impact categories of the life cycles are ozone depletion and human toxicity. The phases of the life cycles for local marble with the highest burdens are energy consumption of the machinery at the extraction site and during the production processes for cutting and polishing the marble. The most crucial interventions are among air emissions: R114 (dichlorotetrafluoroethane), NMVOC, sulphur dioxide, nitrogen oxide and nitrogen monoxide. Moreover, nitrate and nitrogen organic are emitted to water in the process. The source of these emissions has been determined during the conversion of energy which is used very much in marble production.

For limestone, the important impact category of the life cycle is ozone depletion, which is less from the impact of local marble. The phases of the life cycle for limestone with the highest burdens are energy consumption of the machinery at extraction site and cutting the stone during production phase. The most crucial interventions are air emissions: R114 (dichlorotetrafluoroethane), carbon dioxide, sulphur dioxide, nitrogen oxide and nitrogen monoxide, in addition to nitrate and phosphorus emissions to water. The sources of these emissions have been determined during the consumption of energy which is used in limestone extraction, transport and cutting limestone.

Daub stone contribution in human toxicity is higher. The phases of the life cycle for daub stone with the highest burdens are energy consumption of machinery at mining sites and transport. The most crucial interventions are air emissions: NMVOC, carbon dioxide, sulphur dioxide and nitrogen oxide, as well as nitrate emissions to water. The sources of these emissions have been determined during the consumption of energy which is used in stone mining and transport.

12.7 Recommendation

This study can lead the building materials production enterprises and decision makers to improve the present conditions of materials production according to the results obtained here. The results and findings of the current study underline the following recommendations:

- Better environmental performance can be reached in the system by improving the efficiency of the technology in its whole production system (extraction and manufacturing) in order to save energy. In this content, for the clay brick manufacturing, firing and drying lines play a significant role in the environmental impact of clay brick. For local marble and limestone production, the energy consumed in the production processes, especially the cutting block, is a significant issue. Therefore, the implementation of best available techniques in these processes is specially recommended in order to improve the sustainability of the products.
- Transport is a stage to be borne in mind, and depending on the distance to transport raw materials from an extraction location to the production site and/or to the construction site, it can be one of the most predominant stages of the environmental impacts. Therefore, reducing the distance and using transport alternative choices is recommended to reduce the impacts of transport process.

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Chapter 13
A Review on Biofuel and Bioresources for Environmental Applications

Jeremiah David Bala, Japareng Lalung, Adel A.S. Al-Gheethi and Ismail Norli

Abstract Microalgae are considered one of the most promising feedstocks for biofuels. Interest in algae-based biofuels and chemicals has increased over the past few years because of their potential to reduce the dependence on crude oil-based fuels and chemicals. Algae is the most suitable and sustainable feedstock for producing green energy. However, numerous challenges associated with declining fossil fuel reserves as energy sources have accounted for a shift to biofuels as alternative product from algae. Algae is a source for renewable energy production since it can fix the greenhouse gas (CO_2) by photosynthesis and does not compete with the production of food. This chapter, therefore, presents a review on the prospects of algae for biofuel production and also highlighted in this article is the macroalgae-based biofuels energy products obtained from algae as the raw biomass. In a nutshell, algae are the most sustainable fuel resource in terms of environmental issues.

Keywords Algae · Biofuels · Bioresources · Macroalgae · Microalgae · Renewable energy

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13.1 Introduction

In the beginning, the first generation of bioenergy strategies involved biofuel production based on sugar, starch, vegetable, or animal oils using conventional technology [1, 2], but these methods have been globally criticized because they competitively consume food resources [3]. To overcome this problem, the second generation of bioenergy uses non-edible or waste vegetable oils and agricultural wastes such as lumber, straw and leaves which availability are less [4]. Terrestrial bioenergy production systems are now facing issues related to indirect emission and carbon debt from land clearance and hence are becoming a sustainability hurdle for further expansion [5–8]. Therefore, Trivedi et al. [9] has reported that a more sustainable feedstock had to be evolved to overcome these limitations. Microalgae standout as the most suitable and sustainable third-generation feedstock for producing biofuels [9–11].

Methods to convert biomass to competitive biofuels are increasingly attractive as fossil hydrocarbons are likely to become scarce and costly [2]. Interest has now been diverted to the third-generation biomass like algae, since the first-generation feedstocks (edible crops, sugars, and starches) are under serious controversy considering the competition between food and fuel feud [12] and the second-generation biomass (lignocellulosic biomass) are limited by the high cost for lignin removal [2]. Algae is a very promising source for renewable energy production since it can fix the greenhouse gas (CO_2) by photosynthesis. The average photosynthetic efficiency is 6–8 % [13] which is much higher than that of terrestrial biomass (1.8–2.2 %) [2].

Energy security is a major issue faced by countries all over the world. The increasing energy consumption has dropped the fuel resource by maximum. The total global petroleum consumption is still increasing due to intensified energy consumption [14]. In 2007, there were 806 million cars and light trucks [15] which is expected to increase up to 1.3 billion by 2030 and 2 billion by 2050 [16]. Currently, one-fifth of the global CO_2 emission is due to transportation and trucking [14]. It is critical to realize the negative impacts imparted on the global environment by fossil fuels that has drifted the exploitation of alternate fuels. The green replacement of fossil-based petrofuel is the trending strategy that has gained much attention from scientists all over the world. Biofuels have the potential to replace existing conventional fuels, reinforce energy security and reduce the emission of both greenhouse gases (GHGs) and other air pollutants [14]. Biofuels are considered sustainable, renewable, and environment-friendly fuels. Biofuels such as bioethanol, biobutanol, and biodiesel are produced from sugar beet, sugar molasses, soybean, or rapeseed. Biodiesel is alkyl esters obtained from transesterification of fatty acids (FAs) obtained from renewable biomass.

The sustainability revolution is the defining challenge of our time to meet increasing needs in the energy–food–water nexus without compromising the ability of next generations [17]. Sustainable agriculture based on annual grains and perennial high-biomass yield plants along with new biorefineries could produce a myriad of products from biofuels (e.g., butanol and hydrogen), biomaterials, to food. Sustainable agriculture and new biorefineries could be cornerstones of the coming sustainability revolution based on the most abundant renewable bioresource biomass [17]. A variety of biofuels have been proposed, such as cellulosic ethanol [18], n-butanol [19, 20], isobutanol [21, 22], long-chain alcohols [23, 24], electricity [25, 26], alkanes [27], FA esters [28], hydrogen [29, 30], hydrocarbons [31, 32], and waxes [33]. In terms of the entire life cycle, the production of any biofuels from biomass sugars is a nearly carbon-neutral process [34, 35].

Numerous challenges associated with declining hydrocarbon deposit, such as petroleum fuel reserves as energy sources, have accounted for a shift to biofuels as alternatives [36]. Since its early commercialization as a substitute for petroleum-diesel for nearly ten years now, biodiesel as biofuel has remained a good global fuel for running automobile engines [36]. Many interesting factors have been ascribed to this success. Among others, biodiesel is chemically non-toxic in nature, biodegradable, and can simply be prepared via transesterification under mild conditions [37]. In addition to insignificant contribution to CO_2 and other particulate matter emissions, it could be employed directly in conventional petroleum-diesel engines given optimal performance, particularly due to very low sulfur and aromatic contents and compatible flash, cloud, and pour points [37–39]. This article focuses on the prospects of algae for biofuel production and the macroalgae-based biofuels energy products that can be obtained using algal biomass as the raw material.

13.1.1 Developing Bio-based Resources Products

There is a growing urgency to develop novel bio-based products and other innovative technologies that can unhook widespread dependence on fossil fuel. Renewable, recyclable, sustainable, triggered biodegradable bio-based products can make a difference in the environment today and tomorrow. A bio-based product derived from renewable resources having recycling capability and triggered biodegradability with commercial viability and environmental acceptability is defined as a “sustainable” bio-based product [40]. Switching to the use of renewable resources whenever the appropriate technology is available is a more sustainable and environmentally responsible approach. Indeed, the conversion to a bio-based economy will take time, but there is now a major effort underway where plant-/crop-based renewables are serving as complementary resources to conventional feedstocks to meet the ever-growing needs for chemicals, materials, and other products [41]. Biotechnology is key to the continued progress in this area.

Plant-/crop-based (i.e., bio-based) resources are defined as source material derived from a range of plant systems, primarily agricultural crops, forestry products, and processing streams (including microbial) in the food, feed, and fiber industries [42]. Plant-based inputs may take several forms including wood, cellulose, lignin, starch, amino acids, proteins and may be sourced from many different places, e.g., from biomass, crop residue, dedicated crops, and crop processing by-products [42]. The current goal is economic and renewable suites of products from new biorefineries, which will include production of primary products and coproducts together [41]. The primary bio-based products can include oils, commodity or specialty chemicals, and materials.

13.1.2 Developing Renewable Energy Sources

There is now widespread acknowledgment that renewable bioresources have considerable potential to increase national energy security and to minimize anthropogenic effects on the environment. However, the transition to renewable resources from fossil fuels must meet certain replacements in the economic arena. It will require significant advances in science and technology development to both meet such criteria and to ensure sustainable enterprises [42]. There are many options on how to most effectively use biomass to generate energy. A major consideration is the source of biomass. In the USA alone, forestry sources and crop residues are a 260 billion-kilogram source of biomass that is not utilized today [41]. The Minnesota Agri-Power Project uses crop parts in an integrated manner. Some 620,000 metric tons of alfalfa are converted into feed with an additional net energy output [42]. Specifically, the leaves are processed into a high-protein animal feed, while the stems are gasified and combusted to produce 75 MW of electricity per day [41]. Although many biomass materials can be used directly, most require conversion to either ethanol or to biodiesel. Biodiesel is produced from any fat or vegetable oil, such as soybean oil, through the chemical process of transesterification. Both the alcohol and biodiesel can be used as a diluent in commercial fuels.

In the USA, the market potential for the production of ethanol from corn stover (the stock, cob, leaf, and husk) is as high as 38 billion liters if cost of production can be reduced [43]. As noted, the stated issue is economics, but it is really an "available technology" issue. A tremendous amount of research is being conducted on finding more efficient ways to convert biomass to fuels. New second-generation biocatalysts are being evaluated for the simultaneous saccharification and fermentation of biomass-derived sugars for generating fuel ethanol [44]. If the plant-derived material is structural biomass, then certain constituents, such as lignin and cellulosics, predominate and new techniques, such as integrated combustion or organometallic chemistry, may provide opportunities to better utilize this type of source [41].

13.2 Algae

Autotrophic microorganisms such as algae seem to be a promising way out for unceasing energy appetite [45]. Algae can be directly converted to energy [14]. The hydrocarbon content of algae distinctively the FAs and acyl glycerides [46] has the potential to counter the diminishing fossil assets [47]. The oil extracted from algae can be used for biodiesel production. The residual biomass rich in sugar fraction can be used for production of biobutanol and bioethanol by fermentation. The algal cells suspended in nutrient rich water acts as a reliable biomechanism that efficiently converts nutrients and CO_2 to hydrocarbons [14].

The interest in algae-based biofuels and chemicals has increased over the past few years because of their ability to reduce the dependence on petroleum-based fuels and chemicals [9]. Algae is touted to be the most suitable and sustainable feedstock for producing green energy as the whole process is carbon neutral in nature and can also be utilized for environment cleaning applications [9]. The present-day option for immediate and sustainable alternate fuels lies with algal biofuels. Algae are the most sustainable fuel resource in terms of food security and environmental issues [14].

Algae are diverse group of photosynthetic organisms ranging from unicellular (microalgae) to multicellular (macroalgae) forms. They have chlorophyll as primary photosynthetic pigment. Commonly, algal population falls under two broad categories (1) microalgae: microscopic algae that grows in freshwater and marine environment and (2) macroalgae: comparatively large, multicellular organisms that grows in marine environment. There are two main populations of algae: filamentous and phytoplankton algae. These two species, in particular phytoplankton, intensifies rapidly to form algal blooms [48]. Though the main storage compound of these algae is starch, oil can also be produced or induced to accumulate within the biomass. The faster growth rate and greater lipid content of microalgae compared to oilseed crops urge researchers to develop technologies for algae utilization in biodiesel production instead of plant oils [6]. Algae-based biofuel production has very less degree of intrusion in the food versus fuel dispute of tomorrow which is an added advantage [49]. Algae can be cultivated on unproductive or abandoned land [50], and it is also very efficient in utilizing the nutrients from wastewater including nitrogen and phosphorus [11] due to its rapid growth rate and the nutrients can be recycled back to the soil by fertilizing the waste by-products [2].

13.2.1 Microalgae

Microalgae are microscopic, unicellular, and phototrophic organisms that falls under the following categories: (1) diatoms (Bacillariophyceae), (2) green algae (Chlorophyceae) and (3) golden algae (Chrysophyceae). Cyanobacteria (Cyanophyceae) such as *Arthrospira platensis* and *Arthrospira maxima* are also referred to as microalgae. Diatoms are the dominant life form in phytoplankton and probably represent the largest group of biomass producers on earth. Green algae are abundantly found in freshwater than in marine waters. The golden algae are similar to diatoms and produce oils and carbohydrates. Microalgae are efficient producers of lipids and other great metabolites that work by utilizing nutrients in the presence of solar energy [14]. The algal species found suitable for biofuel research includes different species of Chlorells sp., Dunaliella sp., Botryococcus braunii, and Nannochloropsis sp. [51].

Autotrophic microalgae are capable of using carbon dioxide and solar energy to synthesize organics such as protein and lipid for their growth. Most of the production of autotrophic microalgae for biodiesel production occurs in indoor photobioreactors that consumes heavy illumination for photosynthesis [14]. In comparison, heterotrophic microalgae are more flexible for the cultivation condition (can grow under light-free condition) and have been found capable of accumulating higher lipid in the cells. The lipid content of heterotrophic Chlorella protothecoides was 3 times higher than that of the autotrophic ones [52–54]. Microalgae commonly double their biomass within 24 h and biomass doubling time during exponential growth can be as short as 3.5 h and under specific cultivation conditions, their oil content can exceed 50 % by weight of dry biomass [45]. Microalgae require less land for cultivation than terrestrial crops, can grow in non-potable water, and do not displace food crops [46, 55].

Microalgae have been recognized as an alternative third-generation feedstock not only because they remove carbon dioxide from the atmosphere, but also because they contain a much higher lipid content per biomass than other plants [10, 11]. Marine microalgae species growing in seawater can also reduce freshwater consumption [56]. In addition, it can be grown with wastewater which indicates a high environmental sustainability of this feedstock [57]. In finding an appropriate application of algal lipid at industrial level, the FA profile analysis is an important task. Recently, there has been an increased interest in the development of alternative methods that improve FAs profile analysis [9]. These methods involve mainly three criteria: (1) direct transmethylation of lipids, (2) elimination of the need for preliminary extraction steps, and (3) using a single-step derivatization procedure for generating fatty acid methyl esters (FAMEs) to denature the protein fraction [58].

Microalgae have the potential for coproduction of valuable products such as carbohydrates, lipids, proteins, starch, cellulose, polyunsaturated fatty acids (PUFAs), pigments, antioxidants, pharmaceuticals, fertilizer, energy crops [59–61], and natural colorants and also as biomass that can be used as animal feed after oil extraction [9]. The most widely used biofuel is bioethanol, which is produced from sugar-based (sugar beets and sugarcane) and starch-based (corn, wheat, barley, etc.) feedstocks [62], while technology leading to conversion of lignocellulosic materials (bagasse, corn stover, rice straw, switch grass, etc.) into ethanol is still under development [56]. Microalgae are photosynthetic microorganisms that convert sunlight, water, and carbon dioxide to algal biomass [63]. Microalgae are being explored at a faster rate as potential oil source for biodiesel production. About 25,000 species are reported out of which only 15 are employed as commercial oil producers [64]. To this end, microalgae represent an exceptionally diverse but highly specialized group of microorganisms adapted to various ecological habitats. Many microalgae have the ability to produce substantial amounts (e.g., 20–50 % dry cell weight) of triacylglycerols (TAGs) as a storage lipid under photooxidative stress or other adverse environmental conditions [46].

13.2.2 *Macroalgae*

Macroalgae or “seaweeds” are fast-growing multicellular plants growing in salt or freshwater that can reach sizes up to 60 m in length [65]. Seaweeds are lower level plants with undifferentiated roots, leaves, and stems. Seaweeds are classified into three broad groups based on their pigmentation: (1) brown seaweed (Phaeophyceae), (2) red seaweed (Rhodophyceae), and (3) green seaweed (Chlorophyceae) [66]. Macroalgae are photoautotrophic and thus produce and store organic carbons (i.e., carbon sources for biorefinery) by utilizing either atmospheric CO_2 or HCO_3 [67]. Due to the high photosynthetic ability of macroalgae, they have the potential to generate and store sufficient carbon resources needed for biorefinery. Advantages of macroalgae as biofuel feedstock includes atmospheric CO_2 mitigation, entrapment of HCO_3 in the water bodies, thereby reducing the acidic nature of water bodies and acid rain hazards, promoting green fuel for green Earth [14]. Globally, red is the most species-rich group (6000) followed by green (4500) and brown (2000) [68]. Brown algae mainly grow in tempered to cold or very cold waters, and red algae grow especially in intertropical zones. The green algae grow in all types of water environment [69]. Macroalgae is cultivated at present for food production, fertilizers, and hydrocolloid extraction in Asia with China, Korea, Philippines, and Japan accounting for about 72 % of global annual production [70]. Currently, the only industrial product of significance from macroalgae is hydrocolloids extraction [2]. There are several reviews on biofuel production from algae, but they focused on microalgae utilization [69] or only one technique like biogas production from macroalgae [71].

13.3 Energy Products (Biofuels) from Algae as Bioresources

13.3.1 *Biodiesel*

Algae can be used as a feedstock for obtaining a number of energy products. Algal biodiesel is a carbon-neutral fuel, which means it assimilates about as much CO_2 during algal growth as it releases upon fuel combustion [72]. For this reason, algae-based fuels are said to be the most effective and sustainable response to climate change [57]. Biodiesel production from these requires release of lipids from their intracellular location, which should be done in the most energy-efficient and economical ways. Transesterification is the most usual method to convert oil into biodiesel [73]. Transesterification converts raw and viscous microalgal lipid (triacylglycerols/free FA) to lower molecular weight FA alkyl esters [74]. The current trend of carrying out transesterification reactions is through the enzymatic route. Lipase enzymes can be used for transesterification purpose. These enzymatic biocatalysts are of two types: extracellular and intracellular lipases [75]. Particular attention has been dedicated to the use of lipases as biocatalysts for biodiesel production due to their favorable conversion rate obtained in gentle conditions and relatively simple downstream processing steps for the purification of biodiesel and by-products [9]. Algal biodiesel has also been found to meet the International Biodiesel Standard for Vehicles (EN14214). Selection of species for biodiesel production depends on fuel properties and oil content along with engine performance and emission characteristics [76].

Biodiesel has good combustion characteristics and reduces smoke and carbon dioxide emissions by 78 % compared to petrodiesel [77]. Biodiesel production and utilization can promote us forward for a safer living and lights rural development by generating employment opportunities. Biodiesel obtained by various methods such as pyrolysis, dilution, transesterification, microemulsion, and supercritical processes have different qualities and properties [14]. To date, macroalgae biodiesel has been reported sparingly and yields are much lower than those of microalgae [78, 79]. The first report on biodiesel production from macroalgae focused on the comparison of thermochemical liquefaction and supercritical carbon dioxide extraction techniques [80] and another report compared the biodiesel production from both macroalgae (Cladophora fracta) and microalgae (Chlorella protothecoides) and it demonstrated the weaknesses of the former for biodiesel. Macroalgae is usually converted into biooil (lipids and free FAs), and then, the lipids are separated for biodiesel production. The high content of free fatty acids (FFAs) in the oil can restrain the target transformation although the FFAs are also precursor of biodiesel [2].

13.3.2 Biogas

The macroalgae exhibit higher methane production rates than the land-based biomass. Biogas production is not yet economically feasible due to the high cost of macroalgae feedstocks, which needs to be reduced by 75 % of the present level [81]. Microalgal biomass after lipid extraction comprises of proteins and carbohydrates that can be digested via anaerobic means to generate biogas, a renewable fuel [9]. Biogas contains a mixture of gases; mainly carbon dioxide (CO_2) and methane (CH_4). There are four main stages in the biogas production: hydrolysis, acetogenesis, acidogenesis, and methanogenesis [82]. The direct energy recovery during biogas production via anaerobic digestion (AD) could be more profitable when the algal lipid content in microalgae is lower than 40 % [83]. Biogas production is a long-established technology. Biogas production from macroalgae is more technically viable than for other fuels since all the organic components (carbohydrate, protein, etc.) in macroalgae can be converted into biogas by AD, and also the low lignocellulose content make their biodegradation easier than their relative microalgae to produce significant levels of biogas [84, 85].

13.3.3 Bioethanol and Biobutanol

Bioethanol can be fermented from all kinds of macroalgae by converting their polysaccharides to simple sugars and by employing appropriate microorganisms. Since macroalgae have various carbohydrates such as starch, cellulose, laminarin, mannitol, and agar, carbohydrate conversion to sugars and the choice of appropriate microorganisms are pivotal for successful bioethanol fermentation. Some of the species used for ethanol production are Cholorococcum, Chlamydomonas, and Chlorella. Fermentative ethanol production from microalgae such as Chlorococcum and Chlorella vulgaris results in better conversion rates than that of other species [9]. Brown algae is a principal feedstock for bioethanol production because they have high carbohydrate contents and can be readily mass-cultivated with the current farming technology [86–90]. Biobutanol can also be produced from macroalgae through the acetone–butanol (AB) fermentation using solventogenic anaerobic bacteria such as Clostridium sp. [68].

Biobutanol and bioethanol are clean burning fuels and considered environmentally safe as greenhouse gas emission is comparatively lesser than fossil fuels. On combustion, they emit carbon dioxide and water. Micro- and macroalgae are fast-growing carbon-accumulating biomass venturing alcoholic fuel production [14]. Quantity of alcohols obtained from algae is much dependent on the reaction parameters [91]. Bioethanol from microalgae can be produced by fermentation of biomass or direct cellular reactions [92]. Fermentation by B. Custersii produced 11.8 g/L ethanol from 90 g/L sugar in a batch reactor, and 27.6 g/L ethanol from 72.2 g/L sugar in a continuous reactor [93]. Also, results from Tan et al. [94] concluded that E. Cottonii could be a potential feedstock for bioethanol production. Bioethanol and synthetic biodiesel from algal feedstock are two liquid algal transportation biofuels [2]. Extracted algal biomass can be pretreated to convert starch to glucose after which biological hydrolysis is done to produce ethanol. Biobutanol production is generally done by biochemical reactions facilitated by Clostridium species [14].

13.3.4 Isobutanol

Isobutanol is one of the most perfect biofuels for meeting needs of current internal combustion engines (ICEs). It has an energy density similar to n-butanol (i.e., 29.2 MJ/L), approximately 84 % of the energy content of gasoline, is of limited miscibility with water, and is completely miscible with gasoline [95]. The branched structure of isobutanol yields a better octane number than n-butanol. Isobutanol can be produced by glycolysis followed by the Ehrlich or 2-keto-acid pathway [95, 96]. This pathway decarboxylates keto acid, the intermediate amino acid precursor, into isobutyraldehyde and then reduces it to isobutanol [17].

Heterologous pathways for isobutanol production from sugars have been introduced to a number of microorganisms, such as *Escherichia. coli* [23] and *Bacillus subtilis* [97, 98], important industrial microorganisms; *Corynebacterium glutamicum* [99], a bacterium known for its high levels of amino acid production; *S. cerevisiae* [100]; and *Clostridium acetobutylicum* [101], a cellulolytic bacterium that produces isobutanol directly from cellulose. In addition, the isobutanol-producing pathway has been introduced to several microorganisms for producing the desired product from proteins [102] or CO_2 supplemented by solar energy [103] or electricity [104].

13.3.5 Biooil

Thermochemical conversion techniques, including pyrolysis and liquefaction, can convert biomass to liquid biooil [105] quickly. Pyrolysis of macroalgae for biooil, in recent years, has attracted increasing interest. On the one hand, macroalgae can be easily harvested from water and dehydration; on the other hand, pyrolysis is likely to be the most tolerant method to the high ash content of the algae compared to other biochemical methods. Pyrolysis is accomplished at temperatures between 400 and 600 °C and atmospheric pressure but requires dry feedstock. During the pyrolysis process, organic structures are decomposed into vapor phase, gas compounds, and a carbon-rich solid residue (char). The vapor phase then condensed into liquid product called biooil (or biocrude) [2]. Liquefaction is a process by which biomass undergoes complicated thermochemical reactions in a solvent medium to form mainly liquid products. Hydrothermal liquefaction (HTL) is a process using water as reaction medium, carried out in sub-supercritical water (200–400 °C) under sufficient pressure to liquefy biomass for biooil production [106, 107]. The liquid biooil is usually separated by extraction of the reaction mixture with organic solvents such as dichloromethane, trichloromethane, and acetone.

13.3.6 Biomethane

Biomethane from biogas is a fuel source that can be converted to heat and electrical energy on combustion [108, 109]. Combustion of methane in Internal Combustion (IC) engines happens by oxidation of methane. Combined heat and power gas (CHG) engine burns methane to CO_2 completely [110]. Carbon dioxide from biogas and flue gas from combustion of biomethane can be recycled back to the culture system as nutrients [111]. Recycling flue gas and CO_2 from biogas as feed for carbon mitigating autotrophs can take the process in feasible way. Recycling the culture water can reduce nutrient usage by 55 % [112]. Syngas obtained by gasification method is a typical source of methane. Syngas has low calorific value of 4–6 MJm–3 that still can be used to run engines for heat, power and drive turbine for electricity [14].

13.3.7 Biohydrogen

Biohydrogen is a zero-emission fuel considered to be much safer than all other fuels. Hydrogen carries energy that can be used to replace gasoline in the vehicles. On combustion, it reacts with oxygen to give water. Water produced is radiant and energy obtained is lesser than spent in production. Combustion in internal engines can drive out power and electricity useful for beneficial activities. Hydrogen as fuel is used in space craft propulsion as it has the highest heating value. Efficient utilization of hydrogen fuel for running vehicles is been considered as the hot topic in hydrogen combustion science. Electric power of 5HW is generated by utilizing hydrogen at volumetric flow rate of 119.7 mol/h using proton exchange membrane and fuel cell [113]. Biohydrogen production is coupled with fuel cells to harvest energy proficiently [114, 115]. Possibly, hydrogen can be used in fuel cell vehicles (FCV) and hydrogen internal combustion engines (H-ICE) [14].

13.3.8 In Vitro Hydrogen

Hydrogen is the best biofuel for future FCVs mainly due to its cleaner by-product (water) and higher energy conversion efficiency through a proton membrane exchange fuel cell (PEMFC) than an ICE, whose energy efficiency is restricted by the second law of thermodynamics [116]. Hydrogen can be produced from biomass and sugars through chemical catalysis (e.g., gasification [117], pyrolysis [118], gasification in critical water [119], and aqueous-phase reforming [120], dark anaerobic fermentation [121], light fermentation [122], microbial electrohydrogenesis [123], and their combinations). However, all these approaches suffer from low product yields, possibly dirty products, or low productivity. In vitro synthetic biosystems for biomanufacturing are the production of the desired products by assembling a number of purified enzymes or cell lysate and coenzymes [22, 124, 125, 126, 127, 128]. In vitro non-natural synthetic pathways can be designed to produce hydrogen by splitting water powered by the chemical energy stored in a number of sugars [126].

Alternatively, hydrogen can be produced from the biomass sugars cellulose and hemicellulose. In this process, a partial hydrolysis of cellulose mediated by endoglucanase and cellobiohydrolase can produce long-chain cellodextrins and glucose [2]. Cellodextrin and cellobiose phosphorylases can produce glucose-1-phosphate (G-1-P) [29]. Similar to the remaining pathway, all glucose units and G-1-P can be converted to hydrogen [29].

13.3.9 Biojet Fuel

Upon combustion, the aircraft jet fuel produces carbon dioxide (CO_2), water vapor (H_2O), nitrogen oxides (NOx), carbon monoxide (CO), oxides of sulfur (SOx), unburned or partially combusted hydrocarbons, particulates, and other trace compounds. These factors jointly create a challenge for the aviation industry to ensure the security of fuel supplies and to minimize the unwanted harm to the environment. Aviation alters the composition of the atmosphere globally and can thus drive climate change and ozone depletion [129]. The aviation industry is concerned about reducing its carbon footprint by using an eco-friendly fuel for air transport. Renewable jet fuel for the aviation industry, also termed biojet fuels, could reduce flight-related greenhouse gas emissions by 60–80 % compared to fossil fuel-based jet fuel. Green biojet fuel is made by blending microalgae biofuels with conventional petroleum-derived jet fuel to provide the necessary specification properties [130]. The oil of microalgae can be converted into jet fuel by hydrotreatment (hydrotreated FAs and esters, HEFA). This process is also certified according to ASTM standard D7566. The resulting fuel can therefore be used commercially in blends containing a minimum of 50 % conventional jet fuel. This fuel is also referred as hydrotreated vegetable oil (HVO), hydrotreated renewable jet (HRJ) or bio-derived synthetic paraffinic kerosene (Bio-SPK). Currently, research is under way to produce biofuel from microalgal source. Two flights in the past have been tested successfully on the jet fuel made from algae oil [131].

13.4 Prospects of Algae as Biodiesel (Biofuels) Feedstock

Among all single-cell organisms (SCO), algae are as promising as yeast and bacteria. A number of interesting factors have been ascribed to this fact. They are widely available and can be grown anywhere with practical consistencies, thereby limiting any competition with edible vegetable oils. Unlike many energy crops, algae can have up to 100 times more oil content. Theoretically, depending on the strength, algae species can produce up to a yield of 20,000 gallons of feedstock per acre of land [132]. Biofuels from algae feedstock will potentially replace a higher percentage of fossil fuels used as automobile fuels than the other sources. The estimated market size for algae is $425 billions, which is more than twice the expected market size for other traditional biofuels. Thus, the algae options stand a market worth hundreds of billions of dollars.

While biodiesel is considered the main obtainable fuel produced from algae, other important fuels can similarly be produced, thus enhancing their exploitation potentials. Fuels such as methane, hydrogen, ethanol, and biogasoline can be generated from algae. The biomass residues are applicable as sustainable feedstock for combustion. Other important areas of applications for algae include environmental management and production of other products. Algae derivatives have excellent bioremediation properties and therefore suitable for treating waste and sewage water through the removal of toxins and nutrients. Pigments, nutraceuticals, and even fertilizers can successfully be produced from algae [36].

It could be seen that producing oil from algae and subsequently biodiesel as well as other products is considered highly efficient by many researchers [133–135]. The processes of cultivation, oil extraction, and final conversion into biodiesel are basically comparable to those of other edible crops such as soy, sunflower, and palm. It is particularly important to note that, unlike other crops, algae can be cultivated even in harsh conditions, including salty and sewage-receiving areas. On the one hand, macroalgae has high mineral or ash content, mainly comprised of K, Na, Ca, and Mg [136] which is not beneficial for the use of macroalgae as a fuel. On the other hand, the alkali metal can be potential catalyst of hydrothermal process. It is prudent to get high-quality biofuel in large quantities.

13.5 Significance of Algal Biomass for Biofuels

Aquatic biomass could also be used as raw material for cofiring to produce electricity, for liquid fuel (biooil) production via pyrolysis, or for biomethane generation through fermentation [66]. Cell walls of diatoms have been composed of polymerized silica and accumulate oil and chrysolaminarin. The freshwater green algae *Haematococcus pluvialis* is commercially important as a source for astaxanthin, *Chlorella vulgaris* as a supplementary food product, and the halophilic algae *Dunaliella* species as a source of β-carotene. Extracted biomass proposed to be used as fertilizer or animal feed is significant in adding economic value to the process [14]. Coproducts such as pigments, agar, carrageenan, and other bioactive compounds are value-added products that can be removed before fuel conversion of biomass [137]. Methane, butanol, and ethanol can be effectively produced by fermentative digestion of residual algal biomass by selective microorganisms [138]. Though algae are aquatic, they use less amount of water than terrestrial plants [139]. No herbicide or pesticide is recommended in algal cultivation [55]. Growth of algal population in wastewater promotes them as dual-purpose choice for biofuel production and organic load degradation [140]. Biochemical composition of algal biomass can be changed by varying the growth parameters, thus inducing richness of targeted biomolecular fractions in resultant biomass steering to the purpose of cultivation [141].

13.6 Environmental Applications

13.6.1 Biomitigation of CO_2 Emissions Using Microalgae

Biological CO_2 mitigation has attracted much attention in the last few years. A large volume of CO_2 is emitted from the power plants and industries into the environment. Therefore, the use of flue gas emissions from an industrial process unit, as a source of CO_2 for microalgae growth, provides a very promising alternative to current greenhouse gas (GHG) emissions mitigation strategies [9]. Microalgae can fix carbon dioxide from different sources, which can be categorized as (1) CO_2 from the atmosphere, (2) CO_2 from industrial exhaust gases(e.g., flue gas and flaring gas), and (3) fixed CO_2 in the form of soluble carbonates (e.g., $NaHCO_3$ and Na_2CO_3) [142]. Chlorococcum littorale, a marine alga, showed exceptional tolerance to high CO_2 concentration of up to 40 %. It was also reported that Scenedesmus obliquus and Spirulina sp. showed good capacities to fix carbon dioxide when they were cultivated at 30 °C in a temperature-controlled three-stage serial tubular photobioreactor [143]. Microalgae Selenastrum sp. can efficiently utilize both bicarbonate salt and carbon dioxide gas as carbon source in culture media [144]. Microalgal species have a high extracellular carbonic anhydrase activity which is responsible for the conversion of carbonate to free CO_2, to facilitate CO_2 assimilation [145].

13.6.2 Bioremediation of Wastewater and Polluted Soil Using Microalgae

The use of algae for bioremediation of wastewater was first investigated in the 1950s by Oswald and Gotaas [146]. Algae utilize the nutrients present in the wastewater for its growth. The wastewater discharged into the water bodies is hazardous to the environment and can cause various health problems in human beings. One of the benefits of using algae in wastewater treatment is that algae produce O_2 during photosynthesis, which promotes aerobic bacterial degradation of the organic components. Bacterial degradation, in turn, produces CO_2, which promotes photosynthesis and the algal uptake of inorganic nutrients [147]. Algae can be used in wastewater treatment for a range of purposes, such as removal of coliform bacteria, reduction of both chemical and biochemical oxygen demand, removal of N and/or P, and also for the removal of heavy metals [148]. Microalgae can also act as a potential sink for removal of toxic and harmful substances from the soil. Microalgae can help in bioremediation of heavy metal ions such as iron and chromium. The three algal species, *Hydrodictyon* sp., *Oedogonium* sp. and *Rhizoclonium* sp., were used for the bioremediation of heavy metals (cadmium and zinc) present in the wastewater derived from coal-fired power generation [149]. Algae have the capability to sequester, adsorb, or metabolize these noxious elements into substantial level [150]. Microalgae possess different molecular mechanisms that allow them to discriminate between nonessential heavy metals from those essential ones for their growth [151].

13.7 Conclusion and Perspective

The versatility of algae is a promising parameter for them being prompted to be used as a biofuel resource. Algae possess a huge potential for using as a raw material in biorefinery as it is capable of producing a wide spectrum of products. It is the most beneficial feedstock for the production of biofuels and chemicals in the near future. Biofuels from algae would be a cornerstone of the sustainability revolution because it will increase energy security and decrease greenhouse gas emissions. In addition, microalgae have inherent advantages that make them environmentally sustainable compared to first- and second-generation biofuel feedstock. Macroalgae integration into a biorefinery is promising for its efficient conversion to biofuels. However, research must be intensified to identify novel and the most appropriate algae species with high oil contents and fast growth rates in a specific environment. Attention should therefore be directed toward their improved performance and productivity.

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Chapter 14
Energy Recovery by Biological Process

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Abstract Understanding and respecting nature will be beneficial to the environment and can produce sustainable and green technology. Therefore, energy recovery from biological processes needs to be considered because it always respects the nature and the biological or environmental system. This chapter will discuss further about energy production by micro-organisms such as bacterium and algae. Consequently, knowledge and principle about those micro-organisms need to be understood especially regarding the type and mechanism of those micro-organisms to produce recovery energy. This chapter starts with introducing the micro-organisms that are capable of producing and recovering energy. Then, it is followed by the next section, the mechanism and production from biological process, which are considered as energy recovery such as methane, hydrogen and biofuel production. Then, the tools for supporting biological system to produce energy recovery, such as bioreactor and ponds, are discussed in the next section. Subsequently, food for micro-organism, also known as substrate, to produce energy recovery is also discussed in more detail. Finally, sustainability of energy recovery by biological process is highlighted at the end of this chapter.

Keywords Bacterium · Algea · Methane · Biofuel · Hydrogen

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14.1 Introduction

Application of micro-organism for energy recovery is not a new technique, and it was applied a long time ago in India, China and Europe. However, until now, the researchers are interested to understand the mechanism and optimization of energy production. Micro-organisms that are always under consideration for energy production include bacterium and algae. Therefore, the next section will discuss in detail those types of micro-organism.

14.1.1 Energy Recovery by Bacterium

The world today is facing a lot of problems due to pollution that is created by our population. One of the worst problems that happen worldwide is air pollution. Basically, air pollution happens due to gas emission from petrol vehicle cars that use petrol as energy sources and turns it into carbon monoxide, carbon dioxide and other toxic gases as by-products. These gases can lead to the greenhouse effect where it leads to rapid climate change and the global warming effect [1]. One of the best ways to prevent this catastrophic disaster is by replacing non-renewable energy sources into a renewable one. The example of renewable energy for replacing petrol is biofuel. Biofuel is mainly composed of ethanol that is produced by fermentation of bacteria like *Saccharomyces cerevisiae* that produces ethanol as its by-product.

14.1.2 Energy Recovery by Algae

Crude oil is one of the highest valued materials on earth due to its function as source of energy for almost every technology today. The crude oil produces valuable oil such as petrol, kerosene and liquid petroleum gas (LPG) that are being used to move our vehicles, to produce electricity and so on. Today, due to the depletion of these sources, a lot of scientists try to find the replacement for these 'black gold' with renewable energy like biofuel. One of the ways to produce biofuel is by using the algae. Algae are plant cells that undergo photosynthesis to produce oxygen and other by-products, mainly oil content. Today's technology allows scientists to produce biofuel that comes from these plants. Based on the research done in the USA, if they want to replace all the vehicles' fuel using biofuel, they need about 0.53 billion m^3 of biofuel annually [2]. In addition, the algae can produce the highest oil yield compared to other plants. Compared to other plants, the advantage for culturing algae as a source of biomass and the next potential as biofuel plants is that the algae are considered as an efficient biological system for collecting energy from sunray for the production of biological compounds. The next benefit is that algae are simple plants compared to other species. This simplifies the harvesting of oil process for biofuel production. Due to many species of algae, these plants are chosen for their highest yield of oil content and the fastest production in order to reduce the capital costs for biofuel production. The other advantages of algae are that they are easily grown and the algal biomass production can adapt easily into various levels of operational or technological skills [3]. This material uses the carbon dioxide contained in the atmosphere in order to produce biofuel.

14.2 Methane Production Biological Process

Methane has a potential to become renewable energy due of its characteristic supporting for burning process. From burning process, energy can be transformed. A bacterium from anaerobic group has a capability to produce methane by anaerobic digestion process. Anaerobic digestion is the biological decomposition of organic substrates in the absence of oxygen. The objective of this chapter is to discuss the fundamentals of methane production through anaerobic digestion process. Anaerobic digestion has historically been used successfully for stabilizing wastewater sludge before advancing to energy production purposes in the recent years. Ensuring efficient digestion of various feedstocks with varying reactor configurations is no simple task, when wanting to optimize the energy production. Considering the need for emphasizing on a sound understanding of process fundamentals, this chapter will help readers understand the fundamentals of methane production, the various substrates and their methane potential as well as the different reactor systems. The breakdown of organic matter occurs in the presence or absence of oxygen known also as aerobic or anaerobic decomposition, respectively. Anaerobic decomposition happens naturally under water or in the guts of animals or can be induced in airtight containers, vessels and confined spaces. Under engineered conditions, the decomposition of the organic matter and the production of its by-products can be optimized. Optimization of engineered anaerobic process is done by controlling its physical or chemical reactions at high pressure and/or high temperature and the inclusion of selected micro-organisms in the digesters. Figure 14.1 summarizes the anaerobic digestion process in three main stages: hydrolysis, acid formation and methanogenesis.

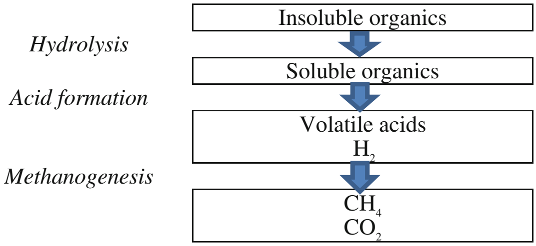

Fig. 14.1 Anaerobic digestion described by three processes

Table 14.1 The composition of biogas [5]

Constituent	Composition
Methane (CH_4)	55–75 %
Carbon dioxide (CO_2)	30–45 %
Hydrogen sulphide (H_2S)	1–2 %
Nitrogen (N_2)	0–1 %
Hydrogen (H_2)	0–1 %
Carbon monoxide (CO)	Traces
Oxygen (O_2)	Traces

Hydrolysis, the first step in anaerobic digestion converts the complex waste into soluble products ready for use by acidogenic bacteria in the next stage. Carbohydrates are turned into simple sugars, proteins into amino acids and fats into long-chain fatty acids (LCFAs). In the acid formation (acidogenesis/acetogenesis) stage, the organic monomers of sugars and amino acids released earlier are degraded by the fermentative bacteria and the obligate hydrogen producing acetogens (OHPA) to produce volatile fatty acids (VFA) (e.g. propionic, butyric and valeric acids) as well as acetate, hydrogen (H_2) and carbon dioxide (CO_2). Ammonia is also produced from the degradation of amino acids. Finally, methane is produced during the methanogenesis stage using the raw materials from the preceding stage. About 75 % of the methane production originates from acetic acid and the closely related acetate, while a lesser amount comes from hydrogen. Anaerobic digestion produces two useful by-products—biogas which can be used for energy generation and a liquid fertilizer or soil conditioner which could be used in agriculture. The term biogas refers to gas that is generated as a result of the action of micro-organisms on the organic wastes [4]. Other definition of biogas includes 'a methane-rich gas that is produced from the anaerobic digestion of organic materials in a biological-engineering structure called the digester' [5]. Biogas (as shown in Table 14.1) is a stable and non-toxic gas which is colourless and does not smell. The gas is flammable when its methane content reached 60–70 % and has a calorific value of 4500–5000 kcal/m^3.

14.2.1 Anaerobic Digestion Feedstock

Historically, anaerobic digestion was employed for the treatment of liquid wastes including domestic or industrial wastewaters, manures and sludge. With the increasing demand for sustainable waste management strategies and renewable energy form, the application for anaerobic digestion has widened to more extensive feedstock selections as shown in Fig. 14.2.

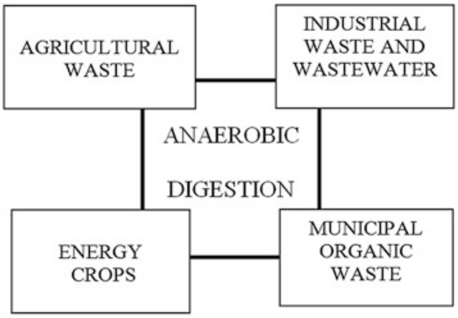

Fig. 14.2 Supply of suitable substrates for anaerobic digestion [15]

14.2.1.1 Agricultural Waste

Several studies have shown that the by-products of cattle, poultry and swine are suitable as feedstocks for anaerobic digestion [6, 7]. The methane potential for pig can be expected to be between 244 and 343 L CH_4/kg VS, while sows are from 260 to 334 L CH_4/kg VS. The average methane potential from dairy cattle slurries is estimated at 243 ± 41 L CH_4/kg VS and is usually lower than the average methane potential from swine slurries at 297 ± 40 L CH_4/kg VS. The methane yields from calves and duck slurries are 386 and 319 L CH_4/kg VS, respectively [6]. The methane potential of livestock waste is influenced by the different organic matter compositions related to animal diet [6]. Cattle are fed with roughage which contains greater amounts of lignin and cellulose than pig feed does. Furthermore, the amounts of proteins and lipids are considerably higher in pig than cattle manure. Due to the higher proportion of lipid in pig manure, theoretically methane would be higher in both pig and sow manure than cattle manure [8]. The amount and type of bedding material also affects the methane productivity of the livestock waste. The use of straw as bedding material (10 g straw per 1 kg manure) has been found to increase the methane yield of the manure by 10 % [8].

14.2.1.2 Energy Crops

Maize is an exemplary energy crop, able to produce methane from 211 L CH_4/kg VS [9] to 300 L CH_4/kg VS [10]. Methane content is usually low with crops having more lignin or with the presence of inhibitors (e.g. tannins and resins in soft woods) [11] but increased with harvest frequency and with leafy plants like napier grass. On the other hand, post-harvest conditions such as ensiling or drying did not have a significant influence on methane yields [11]. Continuing argument exists over the importance of land use for human consumption over energy production, especially for areas where arable lands are scarce, which is indirectly the full-scale adoption of energy crops for energy production.

14.2.1.3 Industrial Waste and Wastewater

The processing of agricultural products, for example wastewater from soya bean [12] and orange juice [13] processing and spent apples from producing apple juice [14], is suitable feedstock for anaerobic digestion, given the huge amounts of wastes generated and its high organic matter. Another possibility is the meat processing industry that emits grease trap sludge which are lipid rich, have small fibrous structure and high water content. Lipids have high methane production potential but when excessive, can be inhibitive due to the production of LCFAs. The fishmeal industry also generates high volume of wastewater suitable for AD, but its elevated sulphide and sodium have to be precautious with suitable adapted inoculum to avoid unstable anaerobic process [15]. One of the drawbacks with most food processing industries as anaerobic digestion feedstock is the seasonal feed variation having an effect on the quality and quantity of gas production. This is because the availability and demand for particular product change considerably during the year.

14.2.1.4 Municipal Organic Waste

The municipal waste that is source-sorted yields biogas 2.5 times more compared to the waste that is commingled [16] implying the sensitivity of substrate biodegradability to the quality of feed by the removal of non-biodegradable portions at the source. Anaerobic digestion of the OFMSW has been demonstrated to proceed best using digested sludge as inoculum and worst if inoculated with cattle manure, causing a restricted removal of organic matter and methane yield [17]. The municipal organic waste steam has been successfully digested at pilot scale under thermophilic conditions, achieving 80 % volatile solid degradation and methane yield of 300–400 Nm^3 CH_4/ton VS at a retention time of 15 days [18].

14.2.1.5 Codigestion

Codigestion can be defined as one of the advantages of the anaerobic technology where several wastes with complementary characteristics are combined in a single treatment. One of the objectives of codigestion is to improve the methane production of feedstock which otherwise if digested on their own would produce a low methane yield due to either its low biodegradability (e.g. due to lignin) or presence of inhibitory compounds such as potassium and lipids. For example, the addition of 40 % (w/w) sludge from an agro-industrial wastewater to fresh vegetable waste (60 %) improved the rate and yield of methane production, which otherwise was not producing biogas because of the excessive potassium (55 kg/kg dry weight fresh vegetable waste) in the vegetable waste. The turnaround to the digestion process was devoted to the dilution and synergic effects [19] from the added sludge. Carballa et al. (2007) compensated the seasonal variations to reactor feeding by combining different fruits and vegetables in the same treatment plant [20]. It was found that the option was viable and the highest methane potential of 465 L CH_4/kg VS was achieved for a combination of tomato, potato and cabbage, while the least was observed with tomato, potato and celery mixture, producing just 235 L CH_4/kg VS.

14.2.2 Anaerobic Reactor Systems

In terms of anaerobic reactor systems, the single-stage continuous reactors have more shares in the market, about 90 % of digesters for solid organic waste anaerobic treatment plants as found in Europe [20]. Of this, 62 % operates at mesophilic temperature. The biogas production for continuous processes is generally higher and more regular than for batch systems as feeding is on a frequent basis followed with the simultaneous withdrawal of reactor. A successful reactor for both waste treatment and energy production should allow for a continuously high and sustainable organic load rate, able to operate with a short hydraulic retention while producing the maximum level of methane yield [21]. A continuous reactor system can be differentiated between a 'one-stage continuously fed systems', 'two-stage continuously fed systems' or 'multi-stage continuously fed systems' and a 'wet' or 'dry' solid waste digesters. If all the anaerobic process occurs in one bioreactor, the system is known as a 'one-stage AD', whereas if a combination of reactors is used, then the system is known as 'two-stage' or 'multi-stage' AD. The latter AD system allows for an increased stability in the process as the acidification stage can be controlled to prevent overloading and build-up of toxic material. The methanogenesis process is also separated and can be controlled independently from the other stages, allowing for enhanced methane yield [22]. For 'wet' or 'dry' digesters, the amount of total solids loaded into the system is the defining factor. Wet bioreactors have total solids of 16 % or less [21, 22], or sometimes contain 10–25 % dry matter as found by Karagiannidis and Perkoulidis (2009) [23]. For dry bioreactors, the total solid content is usually between 22 and 40 % [21, 24], or 30–40 % dry matter as reported by Karagiannidis and Perkoulidis (2009) [23].

14.2.3 Efficient of Anaerobic Digestion

Anaerobic digestion is an efficient waste treatment technology that harnesses natural anaerobic decomposition to reduce waste volume and generate biogas at the same time. It has been widely applied to the treatment of waste from agricultural and industrial operations. Of late, anaerobic digestion has expanded to the combination of organic materials to compensate for the deficiency with single feedstock, as well as the utilization of energy crops for energy production. There are various reactor systems ranging from batch, single-stage and multiple-stage CSTR

Table 14.2 The current research about production and utilization of methane by anaerobic bacteria

Title of research	Details about research	References
Protease cell wall degradation of *Chlorella vulgaris*: effect on methane production	In the study to optimize the production of methane, the enzymatic hydrolysis (protease) process is done to digest *Chlorella vulgaris*. The result shows that enzymatically pretreated biomasses subjected to anaerobic digestion enhanced methane production by 50–70 %	[26]
Enhancement of methane production from codigestion of chicken manure with agricultural wastes	The research states that the mixture of chicken manure and agricultural waste under controlled temperature shows that the production of methane increases by 93 and 50 % compared to control (no AWS added) with maximum methane productionof 502 and 506 mL g^{-1} VS obtained at 55 and 35 °C	[27]
Enhanced methane production of *Chlorella vulgaris* and *Chlamydomonasreinhardtii* by hydrolytic enzymes addition	The effect of protease and carbohydrase shows the high carbohydrates and protein solubilization on both biomasses (86–96 %). The *Chlorella vulgaris* shows the enhancement of methane production up to 14 %, while for *Chlamydomonasreinhardtii*, no improvement was shown. But when the protease used to hydrolyse it, the methane production increases by 1.17-fold	[28]

to a dry or wet reactor systems. The variety in reactor configurations has the intention to optimize methane yield from the digested material making AD a suitable technology in meeting demands for renewable energy. Low-developed countries like India and Africa apply the principal of AD as one of their sources of fuel in the kitchen. Nowadays, the application of biogas already widespread around the globe due to its effectiveness in the production process and awareness on the climate change. For example, in Portugal, the implementation of biogas as one of the source of energy because of to decrease the dependence on fossil fuel and finding the alternative source of new greener energy. The second reasons are the substrates used for biogas fermentation come from organic waste sources such as agricultural waste, sludge and so on. So by using of biogas fermentation, not only it produces energy but it also reduces the waste problems. And the last reasons of the usage of biogas are to reduce the greenhouse effect. By utilizing the methane gas, this gas does not emit to the environment that becomes one of the reasons for the greenhouse effect [25]. Today, there are a lot of research done in the production and utilization of biogas as one of the renewable source energies. Table 14.2 shows the some research on methane production, anaerobic digestion and biogas.

All the methane production discussed above is some of the renewable bioenergy that has higher potential to become one of the major energy sources in the world. By using of plant and algae also biological waste matter, we can reduce the carbon footprint because of all these material uses the carbon dioxide contained in the atmosphere in order to produce biofuel.

14.3 Hydrogen Production from Biological Process

Hydrogen is known as a fuel of the future. Experts list the advantages of hydrogen fuel in its purest form, which include zero emission and endless supply, and production of hydrogen may use a variety of sources including renewable resource [26]. Hydrogen is usually found in a compound which is a combination of oxygen in water or combination of carbon in various hydrocarbon fuels. Once it is extracted, hydrogen is a colourless, odourless and tasteless gas that becomes a useful 'feedstock' or input to variety of industrial activities [27]. Hydrogen-based energy system is intensively developed by the United States (US) government. Key driver to this situation is concern on long-term energy security, environmental quality and economic vitality [28]. Governments around the world seem interested in hydrogen fuel, which leads to various researches in searching for the most affordable way in manufacturing hydrogen. Iceland, Canada, the USA, Japan and Germany have taken the lead in exploring the advantages and benefits offered by hydrogen as an energy source [26]. Hydrogen can be produced from domestic energy resources around the world [29]. Some of the main resources to produce hydrogen include coal, natural gas, biomass, wind, solar and nuclear energy [30, 31]. This topic will only focus on hydrogen production by biological process. The pathway hydrogen production by biological process depends on substrates and micro-organism.

14.3.1 Raw Material for Hydrogen Production

To produce hydrogen via biological process, various waste materials can be used. Kapdan and Kargi (2006) listed a few wastes which can be turned into hydrogen [32].

(i) Starch and cellulose containing agricultural or food industry wastes

Annually, the yield of lignocellulosic biomass worldwide was estimated to exceed 220 billion tons [33]. From this figure, it can be concluded that the lignocellulosic biomass offers attractive and low-cost feed stock for hydrogen production. Lignocellulosic biomass cannot be utilized directly; hence, further pretreatment is required.

(ii) Carbohydrate-rich industrial wastewaters

Some industries discharge wastes are rich in carbohydrate content. Such industries are dairy industry, olive mill, baker's yeast and brewery [32]. Since industrial wastewaters are in use, further pretreatment may be required to remove undesirable component and for balancing the nutrient content. Wastewater may contain varying concentrations of detergent, surfactants and saline, which have different influence on hydrogen production [34].

(iii) Waste sludge from wastewater treatment plants

Waste sludge is rich in polysaccharide and protein and thus is a very suitable substrate for hydrogen production [35].

14.3.2 Pretreatment of Raw Material (Lignocellulosic Biomass)

The utilization of lignocellulosic material cannot be fully adopted because of complicate plant structure which resists microbial attack [36]. To overcome this problem, lignocellulosic material needs to undergo an additional step, which is pretreatment to make the plant structure more readily attacked by micro-organism. Besides that, raw material to produce hydrogen via biological process mainly comes from waste. So, another additional step is mandatory to make sure the raw material is treated accordingly and meet the requirement. The selection of pretreatment method will affect in terms of cost and subsequent fermentation process [33].

(i). Physical pretreatment

The term physical pretreatment implies that this type of pretreatment does not use chemical or micro-organisms. Types of physical pretreatment include comminution (milling and grinding), steam explosion (auto hydrolysis), hot water pretreatment (hydrothermolysis), extrusion and irradiation (ultrasound and microwave) [36]. Zheng et al. (2014) also emphasize that physical pretreatment is suitable to treat organic fraction of municipal solid waste [36].

(ii). Chemical pretreatment

Chemical pretreatment refers to the use of chemicals such as acid and base to alter the structure of the feedstock and chemical pretreatment, which has received the highest research interest [36]. Chemical pretreatment is not only used to pretreat lignocellulosic material but also sludge.

(iii). Biological pretreatment

Among other pretreatments, biological pretreatment is environment-friendly. White- and soft-rot fungi, actinomycetes and bacteria produce peroxidases and laccases to degrade lignin [37]. *S. hirsutum*, one of white-rot fungi species, only degrade lignin rather than holocellulose (hemicellulose + cellulose) and is considered as the most effective way to remove lignin from lignocellulosic biomass [38].

14.3.3 *Process to Produce Hydrogen*

According to Kapdan and Kargi, there are three major processes in which feedstock can be converted into hydrogen via biological process [32].

(i). Biophotolysis by algae

Microalgae, such a green algae (eucaryotic) and blue-green algae or cyanobacteria (procaryotic), have hydrogenase enzyme which can produce hydrogen under certain conditions [39]. In the 1940s, Hans Gaffron discovered the hydrogen metabolism of green algae. He observed that green algae under anaerobic condition can use hydrogen as an electron donor in carbon dioxide fixation process or evolve hydrogen in both dark and light [40]. The photosynthetic decomposition of water into hydrogen and oxygen is called biophotolysis. Photosynthesis is carried out in three main processes which are water decomposed into oxygen, proton and electron in photosystem II and I of chloroplast; electron transportation to ferredoxin through electron-transfer redox reaction; and proton reduction with electrons by hydrogenase or nitrogenase [41]. In Fig. 14.3, Benemann and coworkers demonstrate that hydrogen can be evolved from water by light energy in a reaction that is dependent on both photosystems of chloroplast, ferredoxin and hydrogenase. However, hydrogen production lower compared to the typical rate of carbon dioxide reduction [39]. According to Yoshiharu Miura (1995), the maximum theoretical yield of marine algae produces 4 mol of hydrogen from 1 mol of glucose and the researcher suggested using photosynthetic bacteria to overcome this problem with a maximum theoretical yield of 12 mol of hydrogen from 1 mol of glucose [41].

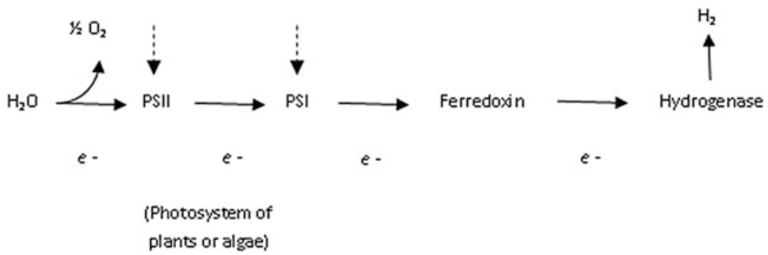

Fig. 14.3 Electron transport pathway to produce hydrogen [65]

(ii). Dark fermentation

Dark fermentation is an anaerobic digestion of an organic matter [42]. As all biological roads are available to produce hydrogen, dark fermentation can utilize various agricultural wastes and is considered as an effective method [43]. The authors also reported that dark fermentation has low conversion efficiency and issue of effluent pollution from fermenter. Besides that, dark fermentation is the key technology to produce hydrogen from crop residual, food waste and livestock waste [44]. According to Das and coworkers, fermentation by bacteria has several advantages, such as very high evolution of hydrogen, hydrogen production can be produced constantly through day and night from organic substrate, and the growth rate is good to supply micro-organism for fermentation. The fermentation can be done in either facultative or strictly anaerobic condition. Various pathways may establish which either inhibit or enhanced the production of hydrogen and govern the production of VFA and alcohol including acetate, propionate, butyric, lactate and ethanol [42]. Theoretically, 4 mol of hydrogen can be produce per mol of glucose [33].

(iii). Two-stage dark/photofermentation

By combining these two processes, the dark fermentation will provide enough organic acids to the photofermentation, the limitation of organic acids can be eliminated, and higher hydrogen production could be achieved [32]. The production of hydrogen by this system is 6.6 mol of hydrogen per mol of starch which is high enough compared to other systems. The organic acid produced during dark fermentation is used by photosynthetic bacteria to further produce hydrogen [45].

14.3.4 Future of Hydrogen

Up to date, many car manufacturers take an initiative to develop a car that can run on hydrogen completely. BMW, Honda, Toyota, Mercedes-Benz and Nissan among car manufacturer that developing hydrogen technology for their car. The most promising car came from Toyota with their Mirai hydrogen car. Mirai has range of 483 km and refuelling in just five minute. This car only emits water vapour, claims Toyota [46]. Massachusetts Institute of Technology (MIT) researcher has just announced that they successfully modified a virus to split water into hydrogen. This virus is called M13 act as ‘scaffolding’. This leads to non-intensive and efficient way to produce hydrogen [47]. As we know hydrogen can be extracted from water by mechanical or chemical process. Unfortunately, in order to get hydrogen gas by extracting the water molecule, we need to use more energy [48]. This renewable energy also gives hope to the world in searching for renewable energy that is zero carbon emission. For the sake of finding new energy, billions of dollars have already been spent to the research and development (R&D) in hydrogen production. Nowadays, there has a way in the production of hydrogen gas by using biological process [49]. There have

Table 14.3 Production of hydrogen gas by using microbe

Title of research	Details about research	References
Acidogenesis characteristics of natural, mixed anaerobes converting carbohydrate-rich synthetic wastewater to hydrogen	The research done by using of mixed anaerobic microbes in the controlled acidified environment to enhance the production of hydrogen gas. The result shows that the production of hydrogen gas higher at pH 5.7 via batch fermentation	[66]
Acidophilic biohydrogen production from rice slurry	The batch fermentation of bacteria from group *Clostridium* sp. shows that at the temperature 37 °C and pH 4.5, the production of hydrogen gas is at the highest rate 2.1 L/(g-VSS d) at 36 h	[67]
Biohydrogen production from biomass and industrial wastes by dark fermentation	The anaerobic fermentation of *Clostridium* sp. is carried out in the dark environment using of food waste as a carbon sources	[68]
Biohydrogen production from wastewater by *Clostridium beijerinckii*: Effect of pH and substrate concentration	The study conducted to investigate the production of hydrogen gas from fermentation of glucose by *Clostridium beijerinckii* in synthetic wastewater. The result shows that the highest production of hydrogen gas is at pH 6.3 and substrate loading of 2.5 g COD/L for the hydrogen production rate of 71 mL H^2/(h L)	[69]
Distinctive properties of high hydrogen producing extreme thermophiles, *Caldicellulosiruptorsaccharolyticus* and *Thermotogaelfii*	The research conducted on *Caldicellulosiruptorsaccharolyticus* and *Thermotogaelfii* in the production of hydrogen gas using glucose as carbon sources. The result shows that the maximum hydrogen production rates are 11.7 and 5:1 mmol/g dry weight/h, respectively	[65]

been a lot of researches done in the production and utilization of hydrogen energy. One of the ways to produce the hydrogen energy is by using microbial activities. Table 14.3 shows the research done for producing hydrogen using of micro-organism.

14.4 Biofuel

There are multiple kinds of renewable bioenergy in the world. One of them is production of biofuel from microalgae. Microalgae are a kind of organism that contains chlorophyll to undergo photosynthesis. They convert the carbon dioxide

Table 14.4 Comparison between microalgae and other biodiesel plants [51]

Plant source	Seed oil content (% oil by wt. in biomass)	Oil yield (1 oil/ha/year)	Land use (m^2 year/kg biodiesel)	Biodiesel productivity (kg biodiesel/ha/year)
Corn/Maize (*Zea mays L*)	44	172	66	152
Hemp (*Cannabis sativa L*)	33	363	31	321
Soybean (*Glycine max L*)	18	636	18	562
Jatropa (*Jatrophacurcas L*)	28	741	15	656
Camelia (*Cameliasativa L*)	42	915	12	809
Canola/rapeseed (*Brassica napus L*)	41	974	12	862
Sunflower (*helianthus annuus L*)	40	1070	11	946
Castor (*Ricinuscommunis*)	48	1307	9	1156
Palm oil (*Elaeisguineensis*)	36	5366	2	4747
Microalgae (low oil content)	30	58,700	0.2	51,927
Microalgae (medium oil content)	50	97,800	0.1	86,515
Microalgae (high oil content)	70	136,900	0.1	121,104

and sunlight into the algae by-product mainly oil-based product. These products can be converted into useful biodiesel with the aid of today's technologies [50]. Table 14.4 shows the difference of biofuel production between microalgae and other plants.

By referring to the table above, there are a lot of advantages of using microalgae for biofuel production compared to other types of plants. The first advantage is the capital cost for growing and harvesting the algae for biofuel is relatively small. Furthermore, algae are not food sources to people. Thus, by using algae as plants for the production of biofuel, the issues on using food as biofuel is already solved [51]. The second advantage of culturing microalgae for the production of biofuel compared to other plants is that microalgae cultivation does not need fertile land for growth. These types of plant can also be grown by using sea water as their sources of nutrient. For the growth enhancement of algae, the nitrates added into the water also increase the growth rate of the algae. Another benefit is that the culturing place for microalgae is relatively small compared to other types of plant [52]. The third advantage of using microalgae as sources for biofuel is the percentages of lipid that are contained in the microalgae that vary based on the species. Usually, the percentages of lipid in microalgae are between 1 % until 70 %. However, in certain species that cultivate in certain conditions, the percentage of lipid contain in cell is up to 90 % [53]. In addition, the growth rate of microalgae is relatively fast. These plants are able to double its biomass within only 3 and half hours [3]. The forth feature of microalgae is that instead of producing lipid as by-product, these plants also produce other types of material mainly in the form of proteins, carbohydrates and biomass. These compounds can be used as a feedstock to animal, or it also can be used as fertilizers. The other advantage of microalgae is that they do not need pesticides to control unwanted pests and diseases that attack on the plants [54]. In order to produce lipid, microalgae must undergo photosynthesis process. In the photosynthesis process, microalgae use carbon dioxide and water and convert it into algal by-product with the aid of solar energy. Due to its microsize, the cultivation process can be altered and done efficiently in order to make the microalgae utilize the sunlight and carbon dioxide in the maximum amount. From the research, it shows that every 1.6 up to 2 g of carbon dioxide is being utilized by every gram of microalgae. Approximately about 180–200 tonnes of carbon dioxide is being used for the production of 100 tonnes of algal biomass [50].

14.5 Substrates

There are several types of substrate that have been identified and can be utilized for energy production using biological processes. Land crops are the first-generation energy/biofuel resources that have been exploited for nearly three decades but have proved completely inadequate to augment rising global requirements. Furthermore, biofuels that can be derived from land crops such as maize, corn, wheat and sugarcane have drawbacks due to global food crisis, large consumption of fresh water and fertilizer, land availability and protection of global ecosystem [55–57]. Then, community has shifted their view to second-generation biofuel technologies to overcome some limitations of the first-generation biofuel, especially their use as food. The demand for renewable energy by using non-edible feedstock has the advantages for practical production of energy. It comprises raw materials derived from lignocellulosic biomass and crop waste residue from various agriculture and forestry processes. They are neither cost competitive nor harmful to environment plus trees is said to contain more carbohydrate than the food crops. By utilizing the breakdowns of plant matter has proven economically and effectively produces more carbohydrates/raw materials for biofuels productions. The drawbacks of second-generation biofuel technologies would be the evacuation of natural deposits from field that will require greater utilization of nitrate manures and consequently expanding nitrous oxide emanations which will affect the biodiversity, land, freshwater and seas by accelerating topsoil losses. Furthermore, digestion of plant materials by using multiple mixture of enzymes is more complicated than digesting one type plant crops [57, 58]. In order to improve the problem arise from

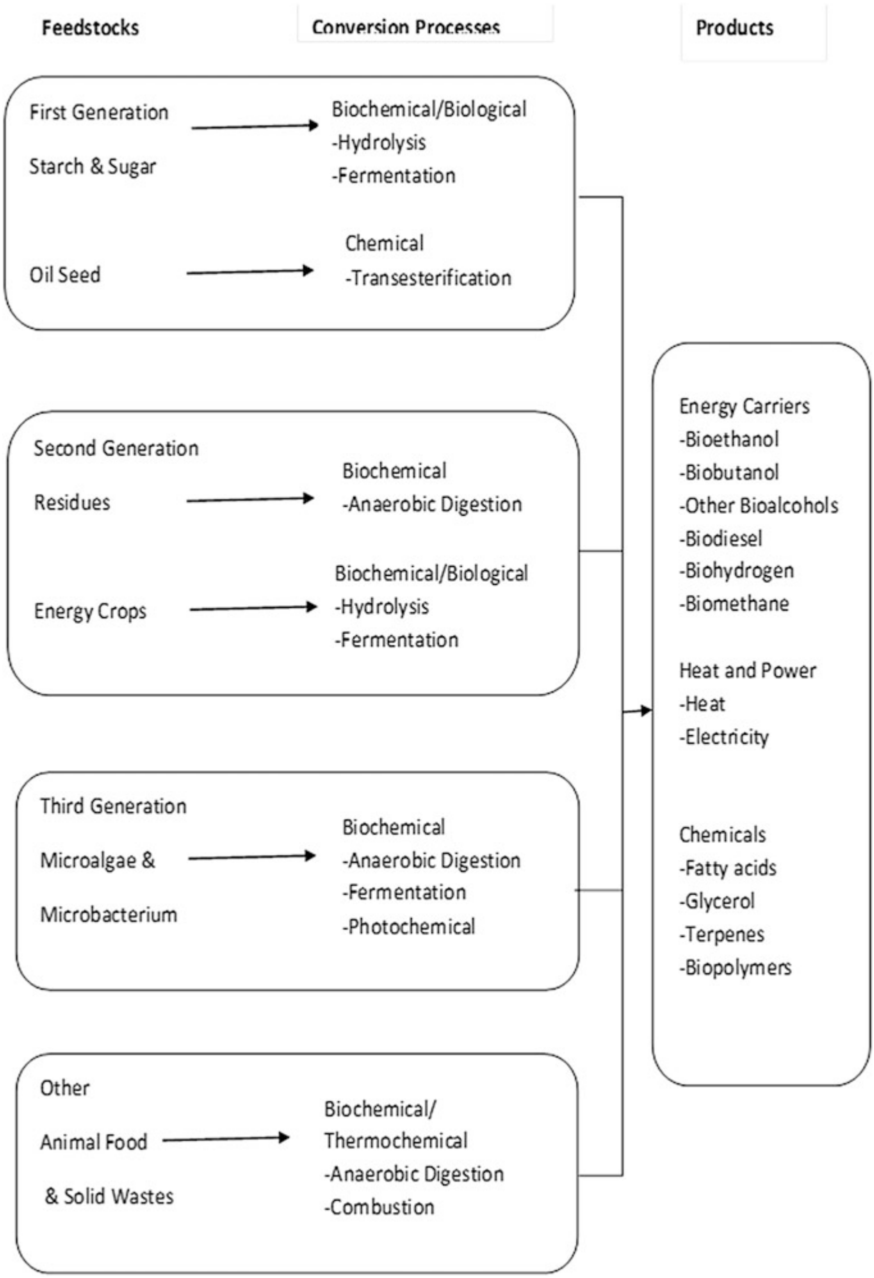

Fig. 14.4 Summary of different type of feedstock, conversion processes and final products associated to biorefinary [55]

first-generation and second-generation biofuel feedstock, the third-generation biofuels has emerged which require less land and can be applied for reducing CO_2 emissions into the atmosphere. These biofuels are derived from aquatic microbial oxygenic photoautotrophs (AMOPs) are commonly known as cycnobacteria and algae and are far more sustainable resource for global demand without affecting the food supply and land-based plant/crops. Among this, biofuels derived from algae appear to have greater prospects being the only renewable energy source especially for fuel transport while addressing the carbon build-up and global warming issue at the same time [56, 59, 60]. Although the third-generation biofuel feedstock being excessively researched and developed for better yield of energy production, there are some other source of materials for energy production such as food wastes, animal food, sewage sludge and leachate from municipal solid waste. Although this resources can easily acquire and free but the size of feedstock are inconsistent with a lot of pretreatment step must be undertaken before the nutrients can be utilized by micro-organism [55, 57]. The summarization of different feedstocks, transformation processes and products is listed in Fig. 14.4.

14.5.1 Biomass

Biomass is a term that encompassess all living or recently passed creatures and their wastes [61]. Biomass has emerged as potential renewable resources for production of fuels, energy or value-added chemical products [55]. The most abundant organic source of carbon on the earth is woody biomass. The forest activity produces large amount of resources and residues daily. The utilization of woody biomass is imperative to the world economy and society [62]. Examples of other biomass include corn, wheat, rye straw, grass and fruit, vegetable wastes, plant-based waste, urban waste, agro-industrial waste and algae [61]. The main advantages of biomass that it is a clean energy source and renewable. Table 14.5 listed all major advantages of biomass and biomass fuel.

Currently, biomass-derived energy sources supply $\sim$50 EJ (exajoule) of world's energy, which represent 10 % of global annual primary energy consumption and $\sim$75 % of the energy derived from alternative renewable energy resources [55]. The most favourable biomass resources are from second-generation biofuels which include lignocellulosic biomass such as crops residue, other non-food energy crops, wood/forestry residues and algae. Lignocellulosic waste is inexpensive, renewable and aboundant and provides natural resources for large-scale and cost-effective bioenergy collection [29, 34]. Component of lignocellulosic biomass can be divided into three biopolymers: cellulose, hemicellulose and lignin. Commonly, most of the agricultural lignocellulosic biomass is comprised of 10–25 % lignin, 20–30 % hemicellulose and 40–50 % cellulose. Commonly, the composition of lignocellulose highly depends on its source whether it is derived from the hardwood, softwood or grasses [58]. Cellulose is a major structural component of plant cell walls that consists of glucose and attached with linear chains up to 12,000 residues, which

Table 14.5 Major advantages of biomass and biomass fuel [70]

• Renewable energy source for natural biomass
• CO_2 neutral conversion and climate change benefits
• Transition to low-carbon economy, namely from hydrocarbon to carbohydrate and H resources
• Use of non-edible biomass
• Conservation of fossil fuels
• Low contents of ash, C, FC, N, S, Si and most trace elements
• High concentration of volatile matter, Ca, H, Mg, and P, structural organic components, extractive, water soluble nutrient elements
• Biodegradable resource with great reactivity and low initial ignition and combustion temperatures during conversion
• Huge and cheap resource for production of biofuels, sorbents, fertilizers, liming and neutralizing alkaline agents, building materials, synthesis of some minerals and recovery of certain elements and compounds
• Reduction of biomass residues and wastes
• Decrease of hazardous emissions (CH_4, CO_2, NO_X, SO_X, toxic trace elements)
• Capture and storage of toxic components by ash
• Use of oceans, seas, low-quality soils and non-agricultural, degraded and contaminated lands
• Restoration of degraded and contaminated lands
• Diversification of fuel supply and energy supply
• Rural revitalization with creation of new jobs and income

is responsible for mechanical strength. Cellulose has a strong tendency to form intra-molecular and intermolecular hydrogen bonds, and this will cause increases in rigidity that makes it highly resistant to most organic solvents. Hemicellulose is a heterogenous polymer mainly consists of glucuronoxylan, glucomannan and trace amounts of other polysaccharides. Hemicellulose and cellulose bind with non-covalent bonds to the surface of each cellulose microfibril, and it believes that hemicellulose to be intermediates in the biosynthesis of cellulose. Lignin has a long-chain, heterogenous polymer composed largely of phenyl propane units most linked by ether bonds. Lignin contains three aromatic alcohols produced through a biosynthetic process and forms a protective seal around the other two components (cellulose and hemicellulose). These groups depend on the plant source which they are obtained [58]. Apart from land-based plant biomass, there is one category of biomass recently being recognized as excellent feedstock for energy production due to their high lipid, carbohydrate or protein content that is algae [55]. In comparison with other renewable sources such as wind, solar, geothermal and tidal energy, algae-derived energy is more controlled and stable compared to land-based biomass agriculture that has the potential to produce more with no fertile land or good water usage [59]. Algae biomass has the high-potential resources for bioenergy industry because of its nature for fast-growing organism and can be grown almost everywhere. The advantages of algae are they do not need large area for cultivation and have a short doubling time (3.5 h) which means it can be 20–30 times faster than food crops [59], and algae biomass contains little or no lignin which will ease the hydrolysis reaction for subsequent fermentation [56]. Most importantly, algae require CO_2 to grow which implies they can be used for bioremediation and biofixation [59]. The organic components of microalgal biomass are mainly composed of 6.7–68.4 % carbohydrates, 14.9–84.0 % proteins and 0.8–63.2 % lipids based on the mass percentage of volatile solids that depends on the species. For macroalgal species, they are composed of 67.0–87.2 % carbohydrates, 9.5–25.4 % proteins and 0–7.6 % lipids based on the mass percentages of volatile solids. The macroalgal species produce relatively high and stable stoichiometric hydrogen yields and contents because of their relatively high-carbohydrate contents and fixed organic components [56]. The algae potential for hydrogen production was known back in 1939 by Hans Gaffron and in 1999 by Professor Tasios Melis with coresearchers from National Renewable Energy Laboratory discovered that depriving the algae of sulphur and oxygen would enable it to produce hydrogen [59]. Microalgae both eucaryotic (such as green algae) and procaryotes (the cycnobacteria or blue-green algae) have hydrogenase enzymes and can produce hydrogen under certain conditions [39]. There are three methods that can produce hydrogen from algae that are biochemical process, gasification and steam reforming. Seaweed or macroalga are a multicellular photosynthetic organism that has the potential to substitute the currently food crop resources as for sustainable production of biofuels and biochemical products. The advantages of seaweed waste biomass are it does not compete with food staples, it reduces or minimizes pollutant loading and it increases the added value of the main product from the carrageenan industry [63].

14.6 Sustainable of Energy Recovery by Biological Process

Today, the world is facing a new global crisis that is energy problem because about 2.4 billion people nowadays are still relying on the old biomass for their sources of energy and more than 1.6 billion are still not getting electricity facilities. In fact, the new global problem arises due to the excessive uses of non-renewable energy by the people that contribute to pollution. This pollution drives our earth into a devastating state where the climate and ecosystem of the earth are changing drastically. Moreover, the depletion of energy sources forces people to find new sources of energy that do not run out and also do not affect our environment [64]. One of the best sources for the energy replacing fossil fuel is biofuel. With the advanced technology today, we can realize our dream to produce sustainable energy without polluting our environment. It is because the biofuel is produced from the plant, which converts solar energy and uses carbon dioxide (sources of greenhouse gasses) for their photosynthesis process to convert it into other products, where the by-products are then converted into biofuel using enzymatic synthesis. One of the problems in this method is that for the first-generation biofuel production, the product produced is mainly focused on bioethanol and biodiesel. These products primarily come from the derivation of food sources such as corn, sugarcane, starches and so on. Moreover, even if the production of biofuel is successful, it also leads to more deforestation and depletion of food sources. In order to overcome this problem, there are some solutions suggested by scientists to enhance the production of the biofuel and at the same time reduce the pollution and replace the raw material that comes from food sources into waste sources.

14.7 Conclusion

Biological process to produce and recover energy is a natural process. Even though it is a natural process, the production can be enhanced to match market demand. The process of supplying, providing and recovering energy by biological process needs to be stressed because it is very complex and sensitive. Furthermore, the application of biological system to recover energy is a green and sustainable technology. It is also very promising in the efforts towards a green environment.

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Index

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