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Review

Integrated Applications of Microalgae to Wastewater Treatment and Biorefinery: Recent Advances and Opportunities

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Abstract

Microalgae is becoming a vital component for a circular economy and ultimately for sustainable development. Herein, recent developments in different outcomes of microalgae for wastewater treatment and biorefinery were reviewed. From its primary function as a third-generation resource of biofuel, the usage of microalgae has been diversified as an integral element for the CO_2 sequestration and production of economically valuable products (e.g., pharmaceuticals, animal feeds, biofertilizer, biochar, etc.). Principles and recent challenges for each microalgae application were presented to suggest a motivation for future research and the direction of development. The integration of microalgae within the concept of the circular economy was also discussed with various routes of microalgae-based biorefinery.

Keywords: *Microalgae, Symbiotic systems, Wastewater treatment, Biofuels production, CO_2 capture, Sustainable development*

1. Introduction

The energy demand is increasing significantly due to the development of heavy industries and the rapidly increasing population. Fossil fuels, including coal, crude oil or natural gas are identified as the basic energy resources and are being depleted due to the continuous rise of energy demand which is still highly dependent on fossil fuels. These fossil fuels discharge many toxic and hazardous gases into the air, damaging the environment[1,2]. After the industrialization period, greenhouse gas (GHG) emissions in the atmosphere have significantly increased. Carbon dioxide (CO_2), among other GHGs such as methane (CH_4), nitrous oxide (N_2O), or other fluoro-hydrocarbons, is one of the primary drivers of climate change through the greenhouse effect[3]. With the finite of fossil fuels and their detrimental environmental effects, the employment of renewable energy sources has become a major motivation of the scientific community.

Biofuels, *viz.* biodiesel or bioethanol, are promising renewable fuels. Biodiesel is synthesized via transesterification of terrestrial crops oils, animal fats, and recycled cooking oils. Its pure form (B100) can be used as fuel for vehicles although it is usually used as a diesel additive to reduce levels of particulates, carbon monoxide, and hydrocarbons in diesel-powered vehicles. Meanwhile, bioethanol is an alcohol produced via fermentation of carbohydrates. It is produced from sugar or starch crops or from cellulosic biomass derived from non-food resources. Its pure form (E100) can also be used as fuel for vehicles. However, it is usually used as a gasoline additive to increase octane value and improve vehicle emissions.

While biofuels offer renewable alternatives to mitigate the drawbacks of fossil fuels, biofuel production is also limited based on its generation classifications. First-generation biofuels made from sugar, starch, or vegetable oil are restricted due to their thread to food security since biomass employed is mostly food crops. This limitation is addressed by second-generation biofuels from non-edible biomass such as wood, organic waste, food waste, and specific biomass crops. However, competition in land use to grow biomass crops can restrict its sustainability. Third-generation biofuels which are from non-edible and non-agricultural biomass (*viz.* algal biomass) show great potential as it addresses the limitations posed by the first and second generation. Microalgae are considered to be one of the best alternatives for biofuel production[4] due to their potential for high oil yields (Table 1) and their ability to grow on non-arable land.

Aside from biofuel production, microalgae also gain attention for CO_2 capture application as it readily converts CO_2 to O_2. As photosynthetic microorganisms, microalgae obtain nutrients from their aquatic habitat, absorb sunlight, and reduce the environmental impact (i.e., freshwater usage) and production cost (due to nutrients requirement),

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Table 1. Typical Oil Yields from Different Biomass[43]

Biomass	Oil yield (L/ha)
Rubber seed	80-120
Corn	172
Soybean	446
Sunflower	952
Peanut	1,059
Rapeseed	1,190
Jatropha	1,829
Coconut	2,689
Oil palm	5,950
Microalgae (30% oil by wt)	58,700
Microalgae (70% oil by wt)	136,900

which are otherwise the limitations on the usage of microalgae for biofuel production, based on some life cycle assessment (LCA) studies on microalgae biofuels. Herein, an overview of the recent developments in the utilization of microalgae, for possible incorporation of wastewater treatment, biofuel production and biorefinery, was reviewed. Achievements in its application for simultaneously production of other economically valuable products such as biofuels, animal nutrition, biochar, biofertilizer, and other biochemical products were also included. This review paper highlights the importance of microalgae and insights into their role in sustainable development, thereby suggesting motivations for future research and development for microalgal studies and applications.

2. Roles of microalgae in wastewater treatment

Conventional wastewater treatment methods include many steps and are costly, which restricts the cost-efficient nutrients removal from wastewater. For example, the anaerobic–anoxic–oxic (A^2O) process, which is the most commonly used biological nutrient removal (BNR) method, requires at least three bioreactors in series (e.g., anaerobic, anoxic, and aerobic) in which working conditions are contrastingly different and complicated[5]. Also, while the activated sludge process is one of the most popularly used wastewater treatment techniques, aeration is an energy-intensive step, and so CO_2 emission during the process could also have environmental implications. When activated sludge is disposed of via drying in a landfill, a substantial amount of energy is additionally consumed and the recycling of nitrogen and phosphorus is minimal. When some amounts of nutrients are still left in the effluent, chemical processes are performed to remove nutrients, which can have increased operation and maintenance costs and cause air pollution due to undesirable by-products such as chloro-organic compounds[6].

Since the 1960s, various types of wastewater have been tested for microalga cultivation. The microalgae-based water treatment technology is one of the most potential technologies to recover the nutrients in wastewater due to its ability to convert it into biomass, especially for the secondary or tertiary steps where it exhibited high efficiencies in nutrients recovery[7]. Nutrients from the wastewater are assimilated for growth, thus reducing the chemical oxygen demand (COD) and the biochemical oxygen demand (BOD) through the oxygen produced photosynthesis of microalgae. In addition, the small size of microalgae provides a large surface area, which increases the nutrient uptake rate in the wastewater.

Sludge concentrate (*viz.*, liquor) which is generated by dewatering activated sludge has received increasing attention since it is an inexhaustible and sustainable resource that can be generated steadily and abundantly by a municipal wastewater treatment plant and it can be used as an additive to secondary-treated wastewater for microalga cultivation due to its high nutrient concentrations. While the concentrations of heavy metals and oxygen content of liquor can be toxic to some microorganisms, microalgae can acclimate to these sub-lethal stresses[8].

2.1. Use of symbiotic interaction

Wastewater contains nitrogen, phosphorous, and carbon substances as well as other macro and micronutrients that are essential for the growth of microalgae cells. Hence wastewater treatment based on microalgae is a promising alternative method. Light and CO_2 can be converted to energy and oxygen during photosynthesis by microalgae. Nitrogen and phosphorous can be assimilated for microalgae cellular functions. Consequently, these processes will reduce the concentration of nutrients in wastewater, while CO_2 can be mitigated. Oxygen by-products can support aerobic bacteria to consume organic compounds in the wastewater. Therefore, microalgae can help minimize the energy requirement for mechanical aeration in wastewater treatment systems[9]. Microalgae growth in wastewater can also reduce the concentration of pollutants while producing microalgae biomass[10].

Recently, many types of microalgae have been applied in the treatment of domestic, agricultural, and industrial wastewaters such as dairy, pulp, aquaculture[10], and piggery wastewaters[11]. In addition, food and dairy manufacturing processes discharged huge amounts of effluents with high nutrient contents which could be useful to growth media for microalgae culture[12].

Symbiosis interaction of microalgae with other microorganisms (especially bacterial species in wastewater treatment) can mitigate the levels of toxic and hazardous pollutants[13]. In this symbiotic relationship, heterotrophic bacteria can utilize O_2 which was synthesized through the photosynthesis process of microalgae cells, to assimilate and degrade organic materials. On the other hand, microalgae can also utilize CO_2, nitrogen, and phosphorus which were released from the aerobic metabolism process of bacteria as nutrients for continuing photosynthesis to increase biomass productivity and repeat the symbiotic cycle.

Aside from treating wastewater and eliminating the risk of eutrophication in water sources, harvested microalgae biomass can be utilized as feedstock in various industries such as energy, cosmetics, pharmacy, or nutrition (Table 2)[14]. Various valuable and bioactive compounds such as lipids, carbohydrates, proteins, unsaturated fatty acids (UFAs), carotenoids, and pigments can also be produced from microalgae biomass. A large amount of essential fatty acids for nutrition like eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) are commercially obtained from various microalgae every year. In addition, fat-

Table 2. Marketable Products from Microalgae Species[14]

Microalgae species	Main products
Arthrospira sp.	Protein: functional food, dietary supplement, or feed for fish farming; Lipids, especially high-value fatty acids (linoleic acid and g-linolenic acid); Pigments (phycocyanin, carotenoids)
Botryococcus braunii	Hydrocarbons; Pigments (violaxanthin, lutein)
Chlorella sp.	Protein: feed for fish farming, cattle, pigs, or poultry
Chlorella vulgaris	Protein: functional food, dietary supplement, feed for fish farming, cattle, pigs, or poultry; Cosmetic purposes
Dunaliella salina	Pigments (b-carotene; bixin, zeaxanthin)
Nannochloropsis oculata	Lipids, especially high-value poly-unsaturated fatty acids

ty acid methyl esters (FAMEs), or biodiesel, can be synthesized through transesterification of accumulated neutral lipids from harvested microalgae biomass.

These advancements demonstrate the multi-functionality of microalgae in wastewater systems. Aside from the primary function of treating the effluent, the wastewater can be an advantageous growth medium for microalgae biomass, consequently decreasing the costs for microalgae cultivation[10]. The novel benefits of employing microalgae in wastewater treatment is incorporating additional functions of biorefinery (including biofuel and other value-added products) and environmental remediation such as CO_2 capture and storage. Microalgae culture in wastewater provides a cost-effective route for producing feedstock for economically valuable bioactive compounds.

2.2. Nutrients uptake

The removal of nitrogen and phosphorus from wastewater is necessary to protect water from eutrophication which can negatively affect the undesirable blooming of aquatic plants. Nitrogen, which includes inorganic and organic nitrogen, is the most important nutrient for cell growth because it appears in the composition and synthesis of all structural and functional proteins, nucleic acids, chlorophylls, enzymes, energy transfer molecules, and genetic materials of algal cells. Meanwhile, phosphorus is also an important factor in the energy transfer of microalgae cells. It is usually found in nucleic acids, lipids, and the intermediates of carbohydrate transfer. Volatilization of ammonia and precipitation of phosphorous can render wastewater treatment more efficient. Since microalga show a very high demand of nitrogen and phosphorous, microalgae have been identified as promising materials for advanced wastewater treatment for the removal of ammonia, nitrate and phosphate. Symbiosis interactions between microalgae and aerobic heterotrophic bacteria can result in high performance in contaminants removal. Microalgae can assimilate various forms of nitrogen including nitrate, ammonium, and organic nitrogen such as urea[15,16].

Cell growth and nutrient consumption are not only affected by the availability of nutrients in wastewater but also by the light density, pH, and temperature. Therefore, cultivation methods can be classified as autotrophic, heterotrophic, and mixotrophic. Autotrophic (utilizing CO_2 as a sole carbon source) is considered to be the simplest and most common for microalgae cultivation. However, many studies have shown that microalgae can grow faster under mixotrophic conditions (utilizing both CO_2 and organic carbons as carbon sources).

3. Cultivation systems

Selecting a suitable microalgae culture system is important for the efficiencies of wastewater treatment and biomass harvesting processes. Conventional cultivation can be performed using two main systems: open systems and closed systems (Figure 1)[7]. The hybrid system

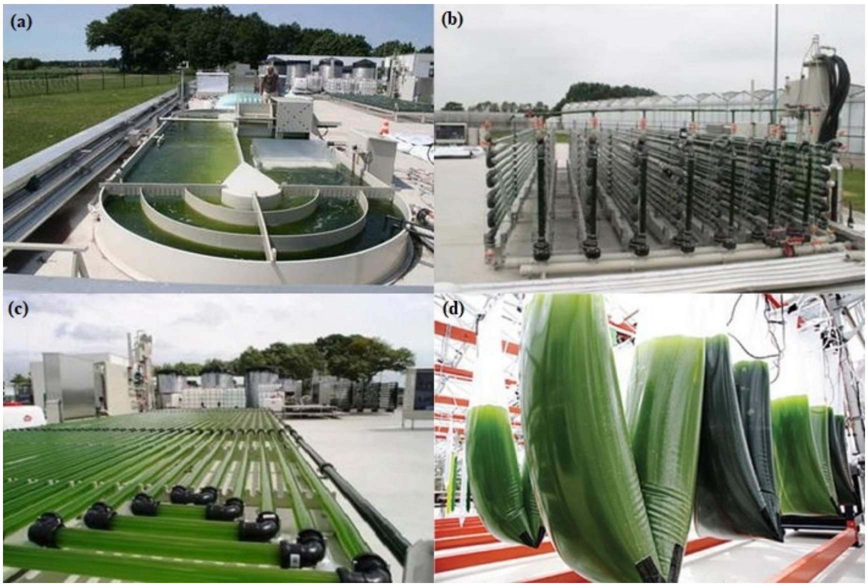

Figure 1. Types of microalgae culture system in industrial scale, including open and closed systems: (a) Raceway pond, (b) vertical tubular PBR, (c) horizontal tubular PBR, and (d) soft frame PBR[7].

combines open and closed systems that can be applied to achieve high efficiencies in nutrient removal and biomass productivity.

3.1. Open systems

Open systems have long been used for large-scale microalgae cultivation due to simple construction and relatively easy operation. The most commonly employed open systems for industrial scale cultivation and research include aeration ponds, lagoons, deep channels, shallow circulating units, and others. Figure 1(a) illustrates a high-rate pond which is a representative type of open pond. Paddle wheels are often installed in the system to ensure the flow of water and aeration while preventing the formation of biomass precipitation. These systems allow microalgae to uptake CO_2 from the air directly from the ambient atmosphere. They are not very expensive and quite easy to clean and maintain from the economic view point. In addition, another advantage of an open system is the good usage of sunlight and its low operational costs[17].

Although open systems require less energy consumption and are simpler to construct and operate than closed systems, microalgae cultures are subject to contamination from outside microorganisms, temperature fluctuation, and water evaporation. For open-design microalgae-based wastewater treatment systems, the excessive evaporation of water can significantly reduce the treatment efficiency. Pollutants or other microorganisms from the surrounding environment can directly introduce and compete for food with microalgae, and ultimately limit the growth of the algal cells. On the other hand, the CO_2 supply may be not sufficient because the content of CO_2 in the atmosphere is only about 0.038%, which limits the rate of CO_2 assimilation of microalgae. The required area to build an open system is also very large, rendering it difficult to deploy. Therefore, adverse conditions may occur in open systems, resulting in very few types of microalgae that can grow under these unfavorable open conditions.

3.2. Closed systems

Closed systems are mainly known as photobioreactors (PBRs). Many researchers have developed the design of closed systems as an advance for higher biomass productivity since they can resolve some problems posed in open systems. There are many configurations available for this application. PBRs can be prepared as flat panels or tubular, and the construction can be made from plastic or glass. Figure 1(b)-(d) shows some typical designs of PBRs such as vertical tubular, horizontal tubular, and soft frame. Tubular PBRs are the most popular design applied on large scale cultivation. The diameter and the length of the reactor as well as the diffusion directly affect the yield of biomass and consumption of energy. The reasonable ranges of energy demand and light availability can be determined and appropriate values of pH, CO_2, and O_2 concentration can be maintained if the tube diameter range is 50-90 mm and the length of the tube is in the range of 100-150 m[18].

Closed systems provide a better light performance for microalgae growth. Due to the absence of external influences, many microalgae species are adaptable to culture in closed systems under different environmental conditions. Moreover, temperature, aeration and stirring can be adjusted easily, thus reducing CO_2 loss and helping microalgae grow more stably and safely. However, the relatively higher cost than open systems can often limit the operation of PBRs for industrial scale needs. There have been reports of microalgae cells sticking to the wall of reactors after a period of culture reducing the light accessibility and leading to the retardation of cells growth. These closed systems are often used for microalgae cultivation and wastewater treatment if the purpose is to produce valuable biochemical products or if the reuse value of the treated wastewater is high enough.

3.3. Hybrid systems

The limitations of open systems related to environmental impacts and low biomass productivity, or the limitations of closed systems related to high installation and operating costs have made address us newer hybrid systems. The cost-effectiveness of hybrid systems allows the cultivation of various species of microalgae at industrial scale. Here microalgae will be cultured in a photobioreactor to achieve high biomass concentration, and then be transferred to an open system to achieve optimal biomass productivity. After cultivation in closed systems, the density of microalgae reaches high enough so that it becomes the dominant species when it is transferred to open systems, which enables us to minimize the contamination of the system[17].

Separation of microalgae biomass from wastewater treatment systems via harvesting is also an important step. The methods usually depend strongly on the nature of microalgae. Typical properties such as the size and the density of cells, and the yield of accumulated products can significantly affect separating potential. Table 3 summarizes some common methods used for microalgae separation from water, including advantages and disadvantages[19,20].

Meanwhile, the rapid growth of microalgae can duplicate the biomass within one day. This rapid growth of cell density can reduce significantly the extent of light penetration through culture medium due to the thick layer of biomass (so called, self-shading effect), thereby retarding the growth of the cells in the farther portions from light irradiation. It is important to employ the circulation of culture medium and microalgae to diffuse light to all cells evenly by improving the de-

Table 3. Harvesting Methods for Microalgae Recovery from Cultivation Broth

Methods	Advantage	Disadvantages
Filtration	High performance for small size biomass	High price, easy to be clogged, and foul
Flocculation	Reasonable cost	Biomass is unstable to use for further purposes
Centrifugation	One of the most effective methods until now, can be up to 95%	High energy demand and operation cost
Ultrasonication	Can operate at a high frequency	Broken cells are difficult to use for further processing

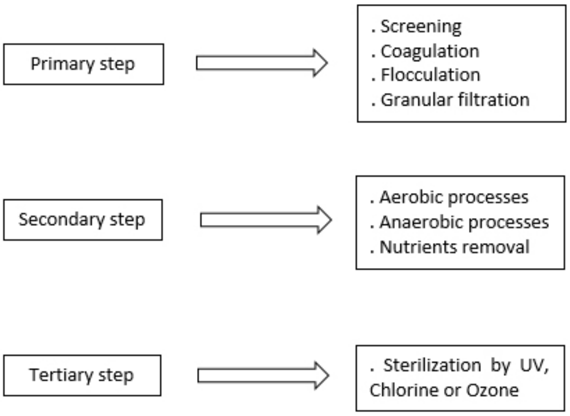

Figure 2. Traditional three-step wastewater treatment process.

sign of PBRs or raceway pond systems.

4. Recent progress in treatment technology

4.1. Bacteria-microalgae symbiotic system

The traditional wastewater treatment systems are comprised of primary, secondary and tertiary steps which include chemical, physical and biological processes (Figure 2). In the primary step, also called the physical treatment step, settled and floating large/solid particles are clarified and removed by coagulation and flocculation in settling tanks or clarifiers. In the secondary step, also called the biological treatment step, aerobic and anaerobic microbes in wastewater degrade organic matters and uptake nutrients. Dissolved solids are also converted to settlable solids. In the tertiary step, the effluent containing some nitrogen and phosphorous is sterilized by chlorine, ozone or UV to ensure no possible pathogenic microorganisms before being discharged.

However, a substantial level of nutrients (nitrogen and phosphorous) in wastewater may not be exhaustively removed through traditional wastewater treatment systems. For the purpose of nutrient removal, microalgae have been considered as a prospective tool of secondary or tertiary wastewater treatment because the microalga-bacteria symbiotic relationship is a natural mechanism of water self-purification and can result in high performance contaminants removal from wastewater (e.g., simultaneous removal of organic and inorganic carbons, nutrients, and heavy metals altogether)[21]. Integrated systems using microalgae-bacteria consortium (Figure 3) have been successfully applied and deemed a promising technique treatment for a sustainable environment, especially for removing nutrients in the effluent. Due to the proven effectiveness of symbiotic consortia, these systems have been reported as viable approaches for the tertiary steps of wastewater treatment[22]. Studies show that the microalgae-employed system has the potential as a replacement for activated sludge processes which have limitation of inefficient nutrient removal and biomass production[15,23].

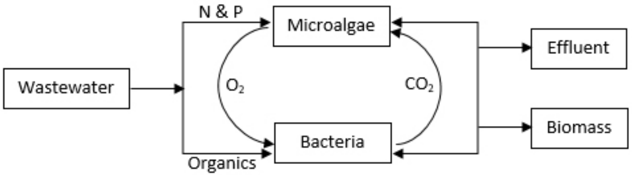

Figure 3. Symbiotic relationship between microalgae and bacteria for wastewater treatment.

Exogenous oxygen which is generated from the photosynthetic microalgae through carbon fixation and nutrients assimilation in the presence of light can be used as an electron acceptor for aerobic bacteria to biodegrade organic pollutants (i.e., BOD). In addition, microalgae treatment can elevate pH and excrete organic matters which can be utilized as an energy source of aerobic bacteria. Heterotrophic bacteria can oxidize organic carbons and mineralize organic compounds in wastewater to produce carbon dioxide and nutrients which can be consumed by microalgae as autotrophic carbon sources through photosynthesis. Bacteria can also release vitamins and plant hormones to stimulate microalgae growth[9,24,25]. *In-situ* oxygenation in symbiotic systems has a potential to meet dissolved oxygen requirements. Therefore, the employment of microalga-bacteria symbiosis can avoid the external supply of O_2/CO_2, reduce the demand for mechanical aeration and thereby decrease the operational cost[26]. Moreover, microalga-bacteria co-culture can remove BOD and nutrients in a single reactor system[27]. Sludge handling after wastewater treatment also becomes easier than activated sludge process because microalga-sludge possesses a good settling behavior. Microalga-sludge can be valorized as an environmentally friendly carrier for nutrients (N and P) recycling[28]. Some unicellular green microalgae species, especially *Chlorella* and *Scenedesmus*, have been identified as potential genus for wastewater treatment due to their high toxicity tolerance, high nutrient removal efficiency and high growth rate in wastewater. Hence, most research has examined these species growth. Piggery wastewater shows great potential as a medium for microalgae growth because it contains a high level of total nitrogen and total phosphorous as compared to some other types of wastewater such as domestic, municipal, or anaerobic digestion effluent[29].

The role of the co-culture system in the nitrification process has been investigated, without mechanical aeration, through the application of a sequential bath reactor mixed with *Scenedesmus quadricauda* microalga and nitrifying bacteria obtained from activated sludge[30]. A mass balance showed that up to 81~85% ammonium was removed mainly by nitrification using the photosynthetically generated oxygen from *S. quadricauda*. The maximum ammonium conversion rate was 7.7 mg/L-h and the oxygen productivity rate was 0.46 $kg/m^3/d$. Better performance for nutrient removal from domestic wastewater was obtained when they employed an algal-bacteria system (ABS) than conventional activated sludge (CAS) system. Under 0.2 L air/min of aeration, TN and TP removal efficiency in ABS significantly increased to 12.13% and 36% compared to CAS under 0.4 L air/min of aeration. Moreover, microalgae in ABS can protect ammonium oxidizing bacteria and nitrite-oxidizing bacteria from optical energy damage.

Gonçalves *et al*.[22] investigated the consortia of *Chlorella vulgaris* microalga with different bacteria (*viz., Enterobacter asburiae, Klebsiella sp.* and *Raoultella ornithinolytica*) isolated from a municipal wastewater treatment plant. The synergistic relationships between these microorganisms boosted the nutrient removal efficiency from a synthetic secondary-treated effluent. As a result, the time required to achieve the effluent discharge limit was decreased to at least 50% of the time required by a single *C. vulgaris* culture. Due to the proven effectiveness of symbiotic consortia, these systems could be considered as viable approaches for tertiary step application in wastewater treatment.

4.2. Immobilized cell system

Recovery of microalgae cells is essential if the biomass is to be reused for continuous operation of treatment reactor or other purposes after wastewater treatment, such as feedstock for biofuels or biofertilizer production. Although many studies have demonstrated that co-culture systems are supposed to be economical and sustainable for wastewater treatment, there are some difficulties related to the physical separation of the microalga-bacteria cells from the effluent after the treatment. If microalgae are immobilized in a matrix, the cells can be easily separated from bacteria and accumulated from the stream. The immobilization technique also can provide advantages such as prevention of biomass washout, higher metabolic activity, and natural segregation[21]. Also, interactions regarding to nutrient consumption may be activated by the entrapment of cells in a small and limited space. Alginate beads were shown to be an economical matrix that can be easily used to entrap microbial cells. Microalgae cells immobilized in alginate beads also exhibited similar nitrogen and phosphorus removal performance as compared to free cells. Anionic functional groups (e.g., carboxyl) of the alginate gel can improve its interaction with the ammonium anion, thereby facilitating the removal of ammonium[25]. Hence, alginate is usually employed to immobilize microalgae cells which also remain highly effective even for an extended period. Ghulam *et al*.[31] investigated the effectivity of green microalga *Chlorella vulgaris* and activated sludge as the co-culture consortium in a bubble column photobioreactor for synthetic municipal wastewater treatment. *C. vulgaris* was immobilized in alginate beads while activated sludge was in suspension, by which simultaneous assimilation of carbon, nitrogen, and phosphorus occurred within a short period of treatment, showing the removal up to 90-99% for COD, NH_3-N, and PO_4-P.

Katam and Bhattacharyya[24] also compared the effectiveness of two different systems: immobilized microalgae and suspended activated sludge (system A) and suspended co-culture (system B) for a domestic wastewater treatment. The results exhibited that the microalgae immobilization technique had more interactive benefits than suspended co-culture system. System A showed higher carbon (88%), nitrogen (91%), and phosphorus (93%) removal compared to system B (87%, 58%, and 80%, respectively). Similarly, Shen *et al*.[32] and Ghulam *et al*.[25] reported a greater removal capability of COD, nitrogen, and phosphorus from municipal wastewater simultaneously by a symbiotic consortium of microalga *Chlorella vulgaris* and bacteria *Pseudomonas putida* using alginate as a granulating agent. It indicated that the nutrient consumption potential of the two species was mutually improved. Ghulam *et al*.[25] confirmed that co-culture with suspended *P. putida* and immobilized *C vulgaris* exhibited the best COD, nitrogen, and phosphorus removal efficiency and that the performance was stable and consistent during repeated runs. The immobilization of one species had more synergistic advantages than co-immobilized or co-suspended cultures.

Meanwhile, Shen *et al*.[32] showed that, under batch culture system, the cell concentrations of *C. vulgaris* and *P. putida* were gradually increased and co-immobilized treatment illustrated the highest nutrient uptake efficiency. On the other hand, Vu and Loh[33] developed a hollow fiber membrane photobioreactor (HFMP) for wastewater treatment by photosynthetic aeration of symbiotic microalga and bacteria. Although *C. vulgaris* was circulated on one side of the HFMP while *P. putida* was separately circulated on the other side, they still support each other in such a closed system. Symbiotic HFMP for wastewater treatment was successful resulting in biodegradation of glucose by utilizing microalgae-generating oxygen. The immobilization of microalgae is an excellent way to prevent the washout of the cells from the treatment reactors and also is an efficient remedy of to achieve cell harvest from the medium and separate microalgae from bacteria.

5. Biorefinery as multifunctional feedstock production

To enhance the environmental and economic benefits of employing microalgae in wastewater treatment, the production of economically valuable products from the recovered algal biomass has long been explored. Thousands of tons of microalgae biomass are produced from wastewater treatment plants or large scale cultivation systems such as open raceway systems. Due to the rich contents of lipid, protein or carbohydrate, microalgae biomass can be a promising feedstock source for biofuels, biochemical, animal nutrition, and biofertilizer production[34, 35]. Toxicity tests are essential if biomass is to be used for the production of cosmetic products, food supplements and animal nutrition, but are not necessarily required for the production of biofuels and biofertilizer. Employment of wastewater as microalgal culture media instead of freshwater can reduce the microalgae biomass production cost significantly while minimizing the environmental footprint.

The biorefinery concept has been considered as a promising way to support the biomass-based industry. If the purpose of biorefinery is to synthesize biofuels and high value-added products, the existing and emerging technologies need to be researched carefully and combined with modern biotechnologies. One of the novel biorefinery approaches is the production of microalgae biomass using flue gas CO_2 and nutrients in wastewater. Conversion of microalgal biomass to different valuable byproducts will not only mitigate CO_2 emission and treat wastewater but microalgae could also play an important role in sustainable development. Studies have shown that many species of microalgae not only convert atmospheric CO_2 into biodiesel but can also accumulate useful compounds for health and food applications. Using exhaust gas and wastewater to cultivate microalgae is a promising way of mitigating CO_2 emissions, purifying water resources, and simultaneously reducing the total cost of microalgae cultivation as feedstock for the production of economically valuable products.

5.1. Biodiesel production

Microalgae can be used as promising resources for biofuel production, including biodiesel, bioethanol, biomethane or biohydrogen[15]. There is a growing interest in microalgae-based biofuel products due to their higher productivity and non-competition with food crops for agricultural land. Particularly, microalgae-based biodiesel has shown a superior yield compared to traditional oil-bearing crops because microalgae can be cultivated in controlled bioreactors, not on arable land. A comparison between biodiesel production from microalgae and oil crops is summarized in Table 4[36]. Processes of biodiesel production from microalgae oil are quite similar to those derived from other energy crops.

Biodiesel does not contain sulfur, thereby the emission of SO_x is greatly reduced during the use. Microalgae biodiesel is also considered to be a carbon-neutral fuel if the amount of CO_2 which is released upon combustion does not surpass the amount it assimilated during algal growth. The fuel specification of the microalgal biodiesel such as density, viscosity, flash point, etc. complies with the limits established by the American Society for Testing and Materials (ASTM) and other countries' standards for biodiesel quality. Microalgae can grow well on low-quality water media such as seawater or wastewaters[37]. Eutrophication in water environment which was caused by excessive nutrients (e.g., nitrates and phosphates) from human activities and loading various wastewaters. However, due to the presence of essential nutrients in wastewater, such wastewaters provide an outstanding alternative and sustainable solution for microalgae cultivation and subsequent biodiesel production.

The synthesis of biofuels from microalgae has attracted much attention due to the increasing need for the reduction of greenhouse gas emissions while diversifying energy portfolio is a desirable strategy of energy supply in many countries[20]. For instance, microalgae harvested from swine wastewater (SW) exhibited distinguished benefits in biofuel production due to their tolerance to and high growth rate in SW as well as high lipid and carbohydrate contents in the obtained algal biomass[38]. Microalgae are also able to remove heavy metals from wastewater[39]. The cultivation of microalgae in wastewater may not only improve the quality of the effluent but can also enhance the economics of biodiesel production from microalgae. Since normally microalgae species with high tolerance to contaminants are selected to grow in wastewater, the potential of using domestic wastewater as an alternative nutrient source to cultivate microalgae is pretty high and currently being explored widely.

The first and second-generation biofuels pose a risk to food security and competition with food crops for agricultural land utilization[40]. Meanwhile, third-generation microalgae-based biofuels not only resolve these ethical problems but also enable us to increase oil yields per unit area higher (Table 1). Lipids in microalga cells are mostly in the form of triacylglycerides (TAGs) which can be converted into biodiesel through a transesterification process mainly as fatty acid methyl ester (FAME) and partially as fatty acid ethyl ester, depending on the involved alcohol. The most common and important reaction used for biodiesel production on a commercial scale involves the replacement of the glycerol backbone of TAG with methanol which esterifies fatty acids[41]. An acid or base often catalyzes the reactions, using a homogeneous or heterogeneous catalytic process (Figure 4). After transesterification, glycerol is generated as a byproduct which can also be used as a resource for pharmaceutical or cosmetic industries after purification[36,42].

Analyzing the fatty acid composition is imperative to identify the suitable application of microalgal lipids and to estimate the final fuel quality at an industrial scale. Researches have been geared to make the biodiesel recovery process easier or to control the fatty acid composition towards more desirable biodiesel quality, such as direct trans-esterification of lipids, reduction or renovation in solvent extraction procedure, and generating FAMEs to denature protein fraction by using a derivatization process[43]. If the main purpose of cultivation is biodiesel production, microalgae species with high lipid content under high growth rate are recommended. Whereas, if it is for bioethanol production, species that can accumulate a large amount of carbohydrates are advantageous.

The swine industry is one of the major industries that releases a huge amount of wastewater (SW) to environment. High concentrations of nutrients and organic contaminants of SW can seriously damage the ecosystem if it is not treated sufficiently. On the other hand, SW is considered a valuable medium and nutrient source for microalgae cultivation, on the way to produce microalgae-based biofuels[38]. Microalgae systems can achieve both a very high extent of nutrient removal and outstanding productivities of biomass, lipid and biodiesel when microalgae are cultivated using SW in photobioreactors. Table 5 shows the lipid and carbohydrate contents, as well as lipid productivity from several studies with different microalgae strains cultivated in SW[44-49]. Lipid contents ranged from 21.4% to 45.8% which is higher than the typical range from usual cultivation under a traditional medium[38]. Kuo *et al.*[50] suggested that the lipid content of microalgae which is cultivated in SW can be increase from 1.5 to 2 times compared to the culture in a traditional medium (Table 4). Same study also showed that the compositions of the main fatty acid (C16-C18) in FAME ranged from 70% to 97.28%, while the carbohydrate contents ranged from 27.6% to 58.3%. These results demonstrated that microalgae, especially *Chlorella* species, could grow well in SW and produce a high amount of biomass that can become valuable feedstock for biofuels production.

Sometimes appropriate extent of environmental stresses may induce the metabolism of lipid synthesis and thus trigger accumulating lipid content in microalgal biomass. The effect of nutrient starvation on the improvement of lipid accumulation (mostly TAGs) has been well explored. Shifrin and Chilhosm[51] showed an increase in lipid content in thirty green microalga and diatom species, including seven *Chlorella* strains, under N-depleted conditions. Illman *et al.*[52] approximated two times rise in lipid content of four among five *Chlorella* strains also in a poor nitrogen medium. Wang *et al.*[53] reported that the lipid content of *Chlorella pyrenoidosa* dropped from 0.22 (g/g) to 0.13 (g/g) when the total nitrogen was increased from 24.5 mg/L to 98 mg/L.

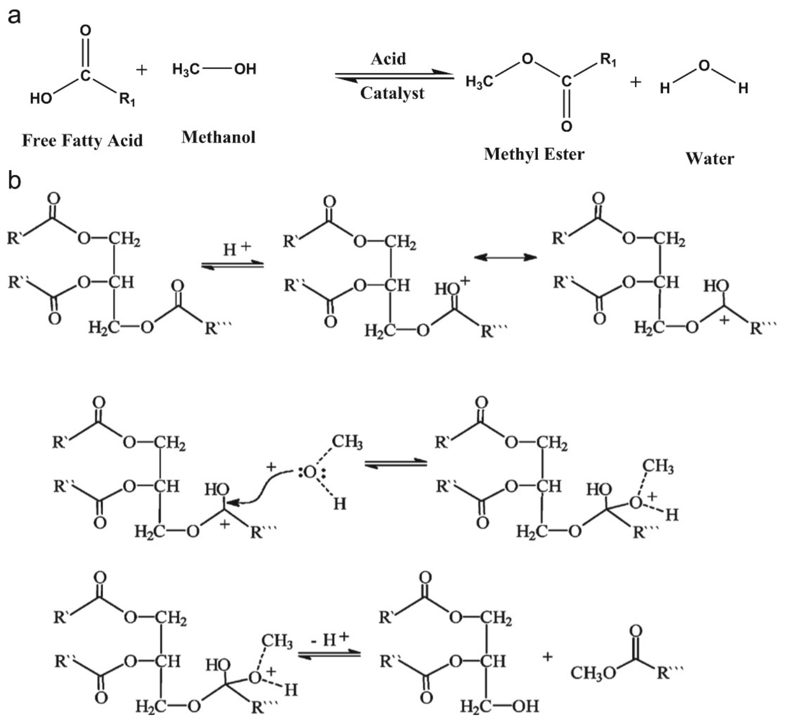

Figure 4. Trans-esterification process using acid catalyst: (a) Overall reaction and (b) mechanism[42].

Table 4. Comparison between Biodiesel from Microalgae and Oil Crops 6[36]

	Microalgae-based biodiesel	Biodiesel from oil crops
Technology	Cell bioengineering is automatically produced in pilot plants	Agriculture in farm
Production period	5–7 days for a batch cultivation	Several months or years
Oil content	More than 50% in whole cells	Less than 20% in seeds or fruits
Land occupied	0.01–0.013 ha for producing 103 L oil	2.24 ha for producing 103 L oil
Cost performance	2.4$ per liter microalgae oil	0.6–0.8$ per liter of plant oil
Development potential	Unlimited (work just beginning)	Limited (works have been done)

Table 5. Contents of Lipid and Carbohydrate of Different Microalgae Species or Strains Grown in Swine Wastewater[44-50]

Species	Lipid content (%)	Lipid productivity (mg/L/d)	Carbohydrate content (%)
Chlorella vulgaris	21.4 - 39.3	100 – 260	
Chlorella zonfingiensis	33.9 – 45.8	490 – 1100	27.6
Chlorella pyrenoidosa	22 – 35.9	6.5	
Chlorella sp. GD	22 – 29.3	155	
Scenedesmus obliquus	27 – 31	720 - 240	36.2
Chlamydomonas mexicana	33	310	
Coelastrella sp. QY01	22.4 – 25.5	130	
Chlorella sp.		514	
Neochloris aquatic CL-M1		820	
Chlorella vulgaris JSC-6			58.3
Chlorella vulgaris CY5			54
Chlorella consortium			58
Scenedesmus sp.			57.6

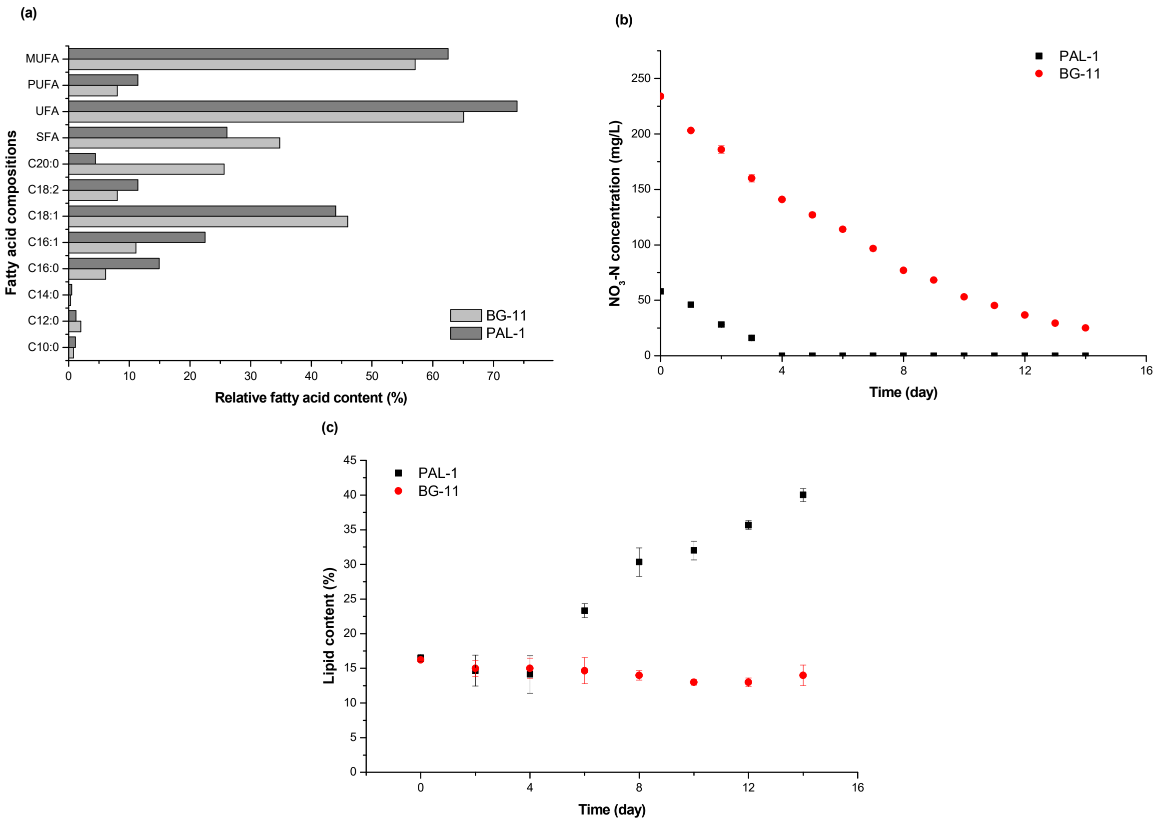

Figure 5. Comparisons in (a) fatty acid compositions, (b) nitrate consumption and (c) lipid content of *Chlorella vulgaris* grown in liquid fertilizer (PAL-1) and defined medium BG-11 (with 2.5% CO_2 supplied)[16].

Organic liquid fertilizer, an agricultural waste, can also be an effective alternative medium for cultivating microalgae for biodiesel production[54]. Figure 5 shows the enhancement of *Chlorella vulgaris* cell growth in a liquid fertilizer compared to the traditional BG-11 medium. The fuel quality of the biodiesel which was produced from the liquid fertilizer was appropriate to maintain both oxidation stability and cold weather fluidity due to adequate proportion of fatty acid compositions (Figure 5a). On using liquid fertilizer as a culture medium, the similar inverse relationship between the lipid content and nitrate concentration was also observed (Figure 5b). Upon complete nitrate consumption (day 4), the lipid content of culture in the liquid fertilizer (PAL-1) immediately boosted and quickly peaked at 48% on the last day of cultivation.

However, the response of microalgae cells to nutrient depletion or repletion can vary depending upon microalgae species. For example, some microalgae strains have been found to increase their lipid content under nitrogen-replete conditions. Increased lipid content of *Ellipsoidion sp.* marine microalga in high nitrate concentration was observed by Xu *et al.*[55]. A separate study by Griffiths and Harrison[56] showed that seven species, among twenty-four green microalgae and cyanobacteria species investigated, exhibited a rise in lipid content under nitrogen-rich conditions. Meanwhile, Kim *et al.*[57] applied a two-stage cultivation system utilizing a nitrate-rich condition with 8.82 nM $NaNO_3$ to improve the extent of lipid accumulation in a marine microalga *Tetraselmis* sp. As a result, the lipid accumulation of *Tetraselmis sp.* was found to increase under nitrate sufficient condition instead of nitrate starved condition. Specifically, after 36 h of the second stage (N-replete stage), lipid content and lipid productivity increased from 22.4% to 30.5% and 26.7 mg/L/d to 47.3 mg/L/d, respectively. These results show that the response of microalgae cells to nutrient depletion or repletion conditions for increasing the lipid amount is species or strain-specific and depends on which condition is stressful to the species or strain we use. In addition, higher light intensity is also considered a factor that can activate and promote cellular lipid storage and can result in an increased lipid content[38].

5.2. Use of algal biomass residue

Microalgae biomass residue after extracting lipids to produce biodiesel can be considered as organic waste to be disposed ultimately and thus its fate of treatment, recycle or conversion to value-added products is important and should be considered in the view of sustainability. After solvent extraction to produce biodiesel, carbohydrates (mainly in the forms of glucose and polysaccharides) and proteins would remain in the residual biomass which can be used as feedstock for producing bioethanol and gaseous or solid form of biofuel[58]. Microalgae biomass exhibits a higher rate of methane production by anaerobic digestion (fermentation) process than other land-based biomass.

There are two main methods of recycling lipid-extracted algal cell residue (LEA) for the purpose of converting it to biofuel: anaerobic fermentation and gasification. Anaerobic fermentation (or anaerobic digestion) process includes four main steps: hydrolysis, acetogenesis, acidogenesis and methanogenesis. The anaerobic fermentation is usually applied to algal biomass residue or intact cells when lipid content is lower than 40% and produces biogas which is composed of CH_4 and CO_2. In gasification, the lipid-extracted microalgae biomass can react with oxygen and steam to generate a gas mixture, called syngas, which includes CO and H_2, high temperature flammables.

Microalgal biomass can also be used as a carbon source for the cultivation of other microorganisms such as bacteria or yeast to produce bioethanol through fermentation. In this process, polysaccharides are broken down into simpler monosaccharides by using suitable enzymes and microorganisms. An important parameter for bioethanol production is to select the right type of microorganisms for fermentation since microalgae include various unusual carbohydrates such as starch, cellulose, laminarin, mannose or agarose. Some studies reported that microalgae *Chlorella* and *Cholorococcum* showed a better conversion rate from LEA to ethanol than other microalgae species[43]. Some studies showed that microalgae biomass can be utilized as a carbon source for biomethane and biohydrogen production through anaerobic digestion and dark fermentation by methanogens and bacteria with hydrogenase activity.

5.3. Animal feeds

Although microalgae biomass is more popular feedstock for biofuels production, microalgae have also gained interest as a nutritional source for animal feeds or aqua feeds. From a nutritional viewpoint, microalgae offer a wide range of carbohydrates, proteins (or amino acids), lipids (or fatty acids), vitamins, minerals, antioxidants and other essential nutrients that are required to animals' growth as compared to other terrestrial plants[59,60]. The supply of distinct microalgae in diets for animals can positively affect animal growth, food security and safety, and can thus improve nutritional quality of meats[61]. Many reports demonstrated the suitability of microalgae as feed supplements. However, microalgae also can easily absorb heavy metals directly and indirectly, which may harm animals and humans. In addition, although microalgae can be used as a good protein source in poultry feed, the long term continuous use may cause side effects on poultry, mostly on the color of chicken skin, shanks and eggs[62].

The utilization of microalgae as feed ingredients for animals can replace traditional food crops and thus reduce food competition with humans. Fish represents about 17% of animal protein consumed over the world. Fatty acids of fish is considered as the best source of *n*-3 long chain polyunsaturated fatty acids (LCPUFA)[61,63]. The use of microalgae as a feedstock for fish food can stabilize the quality of fish protein and *n*-3 LCPUFA supply. Moreover, zooplanktons, one of the most important food in the diet of fish larvae, can be bred feeding microalgae. These show the integral importance of microalgae to the fish ecosystem and related industry.

A good example is the utilization of *Arthrospira,* one of the most widely used microalgae species in the field of animal feeds and that more than 50% of Arthrospira biomass is being used as an animal feed supplement[42]. Some studies reported that *Arthrospira platensis* microalga may significantly increase the weight and improve the growth and body conformation of Australian sheep. Lipid-encapsulated microalgae in the sheep's diets can increase *n*-3 fatty acid content but do not affect milk productivity. Also, feeds containing 5% to 20% *Arthrospira* can provide a rich source of natural carotene pigments to make the colors of many fishes more vibrant which can consequently increase their commercial values[64]. Overall, the inclusion of microalgae in animal food sources is a very promising strategy of biomass utilization, which is both beneficial to livestock industries and microalgae cultivators in a sustainable way. Microalgae biomass can contain a large number of essential minerals and nutrients which are vital for the enhancement of the immune system, fertility, and physical appearance of animals.

5.4. Biochar

Biochar is the solid residue, made of carbon and ashes, remaining after thermochemical conversion (such as pyrolysis) of biomass in an oxygen-limited environment. Biochar is formed when microalgal biomass undergoes a thermal decomposition process at 350-700 °C under an oxygen-limited condition[62,65-67]. Biochar is another valuable product that is obtained from biorefinery process of microalgae. It can act as a bio-sequestrant for CO_2 and as a biofertilizer for soil amendment[68]. Although biochar from microalgae has a lower surface area and carbon content than biochar from lignocellulose materials, the microalgal biochar has a higher ion exchange potential than lignocellulosic biochar[67].

Biochar production is considered as a carbon-negative technology as its CO_2 emission is offset by its CO_2 bio-sequestration. Also biochar from microalgal biomass can be a viable biofertilizer because it contains up to 90% carbon and versatile nutrients. This can enhance plant yields and physico-chemical properties of the land, since it not only supplies high concentrations of nutrients such as nitrogen and phosphorous, but also contributes to maintain appropriate pH value, electrical conductivity of the land, and the particle quality in terms of protein content. Utilizing the biochar as a biofertilizer can reduce the fertilizer costs and the dependence on chemical fertilizers of agro-industries[62].

5.5. Biochemicals for healthcare

Some bioactive biochemical materials have been identified as metabolites of various microalgae species (Table 6). Through appropriate extent of separation and purification processes, they can be excellent value-added products for food supplements and medical purposes[69]. Global companies such as Healthy Care NY, Puritan's Pride, Mera Pharmaceuticals, or Fuji Chemical utilize microalgae biomass to extract possible bioactive compounds which are highly applicable in pharmaceutical, cosmetic, and food industries.

Protein contents of microalgae biomass are in general higher than those of terrestrial food crops, although they are lower than protein

Table 6. Some Bioactive Materials which are Extracted from Microalgae Biomass[69]

Product group	Applications	Examples (producer)
Phycobiliproteins	Pigments, cosmetics	Phycocyanin (*Spirulina platensis*)
Carotenoids	Pro-vitamins, pigments	β Carotene (*Dunaliella salina*) Astaxanthin and leutin (*Haematococcus pluvialis*)
Polyunsaturated fatty acids (PUFAs)	Food-additive, nutraceutics	Eicosapentaenoic acid (EPA) (*Chlorella minutissima*) Docosahexanoic acid (DHA) (*Schizochytrium sp.*) Arachidonic acid (AA) (*Parietochloris incisa*)
Vitamins	Nutrition	Biotin (*Euglena gracillis*) α-Tocopherol (vitamin E) (*Euglena gracillis*) Ascorbic acid (vitamin C) (*Prototheca moriformis, Chlorella sp.*)

contents of animals. Primary metabolites such as protein, carbohydrate or lipid are usually used for growth, while secondary metabolites can serve in the protection mechanisms of organisms. The well-known example is antioxidant compounds such as cyclosporine and dimethylsulfoniopropionate (DMSP), which protect organisms from oxidative stress[70]. These antioxidant materials protect the cells from damaging, by averting the accumulation of reactive oxygen species and free radicals, and thus attract a great attention of cosmetics and skin-care industries. Microalgae also contain a range of vitamins such as vitamin A, B1, B2, B5, B6, B9, B12, C, E, nicotinate and biotin, which are important as food supplements for human health.

However, only a few microalgae strains are used for humans so far because of food safety rules, market demand and commercial factors. The most common species utilized for human health area are *Arthospira*, *Chlorella*, *Dunaliella* and *Nostoc*, and their dried biomass or extracted products dominate the commercial applications. Some cosmetic industries invested to the cultivation systems for *Arthospira* and *Chlorella*, particularly for the purpose of develop beauty and skincare products such as anti-aging agents, UV protect or remedies for skin irritations. Some species of the *Spirulina* genus including *S. platensis* and *S. maxima* are cultivated as a source of human food additives because they not only supply proteins but also can improve immune system and boost body hormones by stimulating lactic acid bacteria in the gastrointestinal tract[71]. *Chlorella* cells have a high protein content (up to 51 − 58% dry weight) as well as carotenoids and vitamins, making them a great resource of food additives.

In the field of medicine, 1,3-glucan which exists in the extract of *Chlorella* is an essential organic compound, which acts as a boosting agent of the immune system, an antioxidant and as a cholesterol reducer. 1,3-Glucan is also known to improve the functions of the digestive system as anti-stomach ulcer and treatment for wounds and constipation[43]. Furthermore, extract products from *Chlorella* species can decrease sugar and cholesterol levels in the blood while increasing the density of intestinal bacteria and stimulating the immune system. *Dunaliella*, a special microalgae species which are capable to grow in brackish water, is also a great food source of protein, glycerol and β-carotene. Carotenoids including β-carotene from *Dunaliella* species were proven to be effective against cancer cells[72]. *Nostoc* species have long been used in China as food and traditional medicine due to their high content of protein and pigments[72-74].

6. Biological CO_2 fixation

Aside from being used for biofuel production, microalgae have long been recognized as a potential tool for greenhouse gas mitigation. This is mainly due to their efficiency of carbon dioxide fixation[75]. Microalgal photosynthesis is an effective approach for biological CO_2 sequestration. They contain chlorophyll, a photosynthetic pigment. The photosynthetic and autotrophic microalgae have high capabilities to sequester CO_2, showing 10−50 times more efficient than terrestrial plants even with high-CO_2 streams such as flue and flaring gas[42].

During photosynthesis, CO_2 functions as a carbon source to microalgae. In the presence of solar energy, CO_2 and water are converted into carbohydrates with the help of chlorophyll yielding molecular oxygen. It involves two steps: light reactions that only occur when the cells are illuminated and carbon-fixation reactions, also known as dark reactions, that occur both in the presence and absence of light[76]. Approximately 1.83 kg of CO_2 can be absorbed to produce 1 kg of microalgae biomass[77]. This renders microalgae an efficient agent for CO_2 bioconversion. *Chlorella* and *Nannochloropsis* species are promising for the production of biomass and biodiesel as they sequester a high percentage of CO_2[78]. *Chlorella* species can grow in freshwater under 40% CO_2 environment at a wide range of temperatures (5~30 °C). *Nannochloropsis* species also demonstrated a high CO_2 fixation rate, showing 0.42 g of CO_2 sequestered per gram of biomass per hour (g/g/h) when cultured in a modified stirred tank photobioreactor[79].

The amount of CO_2 in atmospheric air is too small to use for rapidly growing microalgae due to the limited mass transfer. Meanwhile, flue gases of fossil fuels typically contain up to 15% CO_2 which is approximately 400 times than atmospheric CO_2 concentration. This renders flue gases as an outstanding CO_2 source for microalgae growth and enables us to resolve CO_2 mitigation and wastewater treatment simultaneously[17,80]. However, microalgae growth can be inhibited by direct feeding of flue gas due to sudden stress caused by high temperature (>150°C) and the existence of SOx and NOx. In order to tackle the high temperature limitation, microalgae can be mutated to make them resistant to the heat emitted from factories, or we may select some acclimated microalgal species that are tolerant high temperatures. Some strains of *Chlorella* isolated from hot springs in Japan were observed to withstand temperatures up to 42 °C in air containing more than 40%

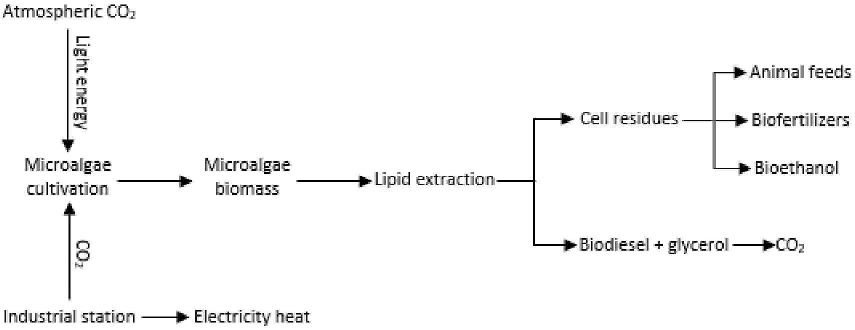

Figure 6. Scheme of novel environmental and economic functions of microalgae for sustainable development.

CO_2[81]. It is believed that native microalgae species are more tolerant to local conditions[82]. Kumar *et al.*[83] tested biomass production using *Chlorella* species grown in kitchen sewage wastewater with CO_2 supply as flue gas collected from a coal-fired boiler. The maximum biomass concentration obtained was 0.6 g/L with nutrient uptake up to 65% and organic matter reduction of 75%, demonstrating that the simultaneous cost-effective sewage treatment and flue gas CO_2 sequestration was achieved by using microalgae.

Dried microalgal biomass can be processed into new configuration of solid materials which possess physico-chemical properties suitable to efficient CO_2 capture. Durán *et al.*[84] prepared activated carbons from four selected microalgae species, pelletized them, and tested them as CO_2 adsorbents. Results showed that the CO_2 adsorption capacities of *Chlorella* and *Spirulina* were 1.55 and 1.49 wt.%, respectively (at T = 50 °C; P_{CO2} = 10.5 kPa). The blends of *Spirulina* microalgae and pine sawdust also exhibited CO_2 absorption capacity up to 4 wt.% under the same conditions. These results demonstrated that activated carbons produced from microalgae, especially when mixed with appropriate sawdust can be a promising CO_2 adsorbent from flue gases. This approach amplifies the environmental and economic importance of employing microalgae as an essential tool of integrating wastewater treatment, feedstock production and CO_2 sequestration (Figure 6).

Generally, the high cost of nutrients, particularly carbon, nitrogen and phosphorus sources, is a major obstacle to scaling up of microalgae cultivation. Bio-mitigation of CO_2 emissions provides an additional opportunity to improve the cost issues of microalgae cultivation and related applications. In order to improve economic feasibility and environmental sustainability of microalgae-employed system, it is inevitable to integrate CO_2 capture with wastewater treatment via microalgae culture and to recycle the resulting biomass for the production of biofuels or other value-added materials.

7. Summary and conclusions

Biorefinery is an industrial process where biomass is converted to bioenergy and high-valued products[14]. The concept is similar to an oil refinery where fuels and chemicals are fractionated or produced. It is an integrated and multifunctional process in which biomass is separated and pretreated first, and then converted to valuable products in the second step. The main purpose of the biorefinery is to combine the production of higher chemicals and bio-commodities with the production of fuels and energy, to utilize all raw materials efficiently and prevent the possible loss of resources. In biorefinery process, resources are saved while the environmental impact is minimized[85].

As previously discussed, microalgal biomass has a good potential of synthesizing multiple products and thus it is considered as a promising raw material for setting up biorefinery. An ideal biorefinery can take advantage of the diversity of biomass components which are capable to extend to value-added materials. The microalgae-based biorefinery can bring more environmentally friendly products while increasing environmental sustainability by reducing greenhouse gas emissions and fossil fuel consumption. The combination of microalgae-based wastewater treatment and biorefinery may create an integrated ecosystem in which end-products are mutually recycled and so required resources are cross supplied each other. Benefits of microalgae cultivation are contributed into allied industries, resulting in enhancing resource management flexibility and saving overall costs. Figure 7 illustrates a schematic example of a microalgae-based biorefinery[14]. CO_2 is captured from flue gas streams and nutrients (or contaminants) in wastewater are utilized simultaneously to produce microalgae biomass at the most economical way. Microalgal biomass residue which is generated after oil extraction for biodiesel can be subsequently utilized as animal feeds, biochar/biofertilizer, or feedstock of bioethanol and/or biogas production.

This study assessed the roles of microalgae as a potential renewable bioresource not only for environmental applications such as wastewater treatment and CO_2 sequestration but also as valuable feedstock for bioenergy, human health, and aquatic and animal nutrition. Wastewater which contains rich nutrients has been identified as an appropriate medium for microalgae cultivation. The utilization of microalgae to remove nutrients (especially nitrogen and phosphorus) from wastewater is a green technology that reduces or replaces the use of chemicals in wastewater treatment plants. The obtained biomass can be further processed to produce biofuel and other economically valuable byproducts. The combination of wastewater treatment, CO_2 sequestration, production of biofuels and other biochemicals provides an attractive strategy of environmental remediation and water resources management simultaneously, allowing more economic feasibility and environmental

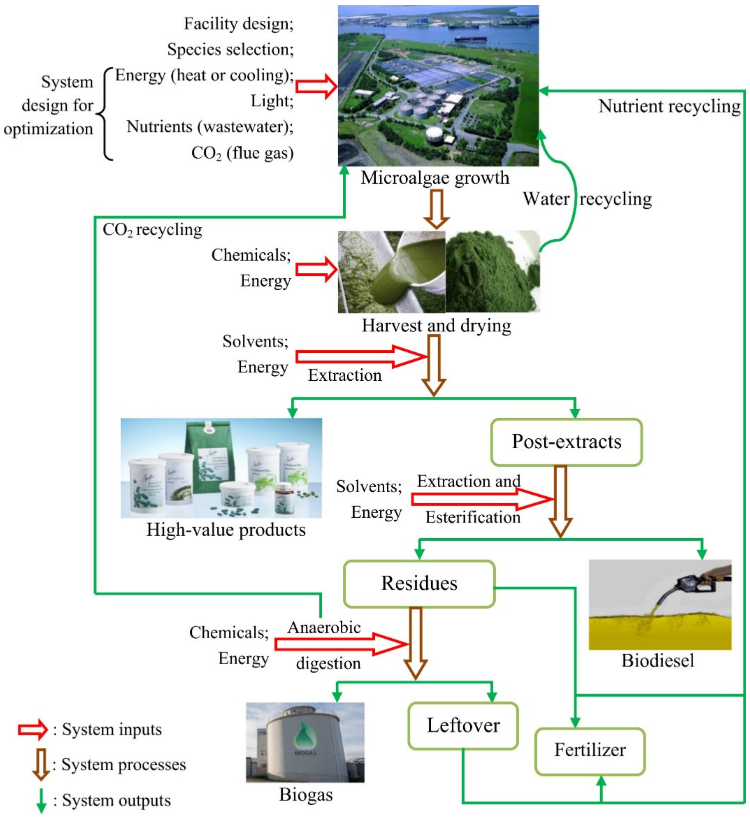

Figure 7. Integration of wastewater treatment, CO_2 fixation and biorefinery by employing microalgae cultivation[14].

sustainability for microalgae-based biorefinery.

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