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Review

Resource recovery from industrial effluents through the cultivation of microalgae: A review

Shazia Ali [a], Angela Paul Peter [a], Kit Wayne Chew [b,c], Heli Siti Halimatul Munawaroh [d], Pau Loke Show [a,*]

[a] *Department of Chemical and Environmental Engineering, Faculty of Science and Engineering, University of Nottingham Malaysia, Jalan Broga, 43500 Semenyih, Selangor Darul Ehsan, Malaysia*
[b] *School of Energy and Chemical Engineering, Xiamen University Malaysia, Jalan Sunsuria, Bandar Sunsuria, 43900 Sepang, Selangor Darul Ehsan, Malaysia*
[c] *College of Chemistry and Chemical Engineering, Xiamen University, Xiamen 361005, Fujian, China*
[d] *Study Program of Chemistry, Department of Chemistry Education, Universitas Pendidikan Indonesia, Jalan Dr. Setiabudhi 229, Bandung 40154, Indonesia*

HIGHLIGHTS

- Microalgae are fit for wastewater treatment due to their high nutrients content.
- Microalgae are cultivated to restore value-added products such as bio-fuels.
- Anaerobic digestion is an important biotechnology for stabilizing waste effluent.
- Hydrothermal processes are an advanced recovering technique for value-added product.
- Biotechnology such as ultrafiltration reduces electric energy consumption.

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ABSTRACT

Industrial effluents such as pharmaceutical residues, pesticides, dyes, and metal processes holds abundant value-added products (VAPs), where its recovery has become essential. The purpose of such recovery is for sustainable treatment, which is an approach that considers the economic, social, and environmental aspects. Microalgae with its potential in the recovery process from effluents, can reduce energy usage of waste management strategies and regenerate nutrients such as carbon, phosphorus, and nitrogen. Microalgae cultures offer the use of inorganic materials by microalgae for their growth and the help of bacteria to produce biomass, thus, resulting in the absence of secondary emissions due to its ability to eliminate volatile organic compounds. Moreover, recovered bioactive compounds are transformed into bioethanol, bio-fertilizers, biopolymer, health supplements and animal feed. Therefore, it is significant to focus on an economical and efficient utilization of microalgae in recovering nutrients that can be further used in various commercial applications.

1. Introduction

Microalgae have a simple cell structure and require light, carbon dioxide, water, and nutrients in order to grow. It is considered as microorganisms that evolve by photosynthesis which can be further categorized as either prokaryotic or eukaryotic (Zullaikah et al., 2019). Microalgae absorb a considerable amount of carbon dioxide, resulting in a larger release of oxygen into the atmosphere via photosynthetic reaction. Carbon dioxide can be obtained on a large scale from an emission point source upstream of a microalgae growing system, such as a power plant, which allows for the recycling of exhaust gases (Davis et al., 2011). Microalgae may produce large quantities of biomass and have a high oil content, which can be used as a feedstock for biodiesel production and have been suggested as a potential source of renewable energy (Kothari et al., 2017).

Microalgae's great versatility and adaptability to grow in a variety of habitats as it requires less arable land than terrestrial plant areas. It can be grown in areas that require treatment for its constituents such as various effluent system in domestic, industrial, and agricultural sectors. Environmental benefits from microalgae includes the removal of

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* Corresponding author.
E-mail address: pauloke.show@nottingham.edu.my (P.L. Show).

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contaminations from the result of human activity, such as the production of batteries, paints, and metal alloys, as well as the production and consumption of fossil fuels and mining. Metal ions such as cadmium, copper, lead, mercury, and chromium have harmful effects on aquatic flora and animals, and it accumulates in the food chain (Tchounwou et al., 2012).

Moreover, waste that are overflowing and gets in contact with human as it contains microorganism that causes illness and viral infections (Tomei and Angelucci, 2017). Wastewater from irrigation as part of agro-industrial sectors contains nutrients needed for plant growth, and when discharged, it may cause harmful effects to the environment by eutrophication which is the alarming growth of plants in water bodies that take up space and oxygen for their growth, leaving other organisms suffocating (Lemley and Adams, 2018). Therefore, microalgae provides a green alternative in treating waste

Effluents collected as waste active sludge contains nutrients with the presence of high organic substances. These nutrients are known as value-added products where their organic substances can be reused for various applications that will conserve natural resources and increase economic security (Oputu, 2017). Wastewater from different sources contains multiple nutrients, but mainly nitrogen, phosphorus, potassium, proteins, ammonium, and fatty acids (Ma et al., 2018). Furthermore, as a by-product of wastewater treatment, microalgae release oxygen, which is used by aerobic bacteria to further degrade the residual organic loads. As compared to the cost of mechanical energy for aeration during traditional wastewater treatment, this saves energy (Amenorfenyo et al., 2019). Several innovative advances have opened the way for utilities to control better and improve their operations using green-based technologies around value-added product recovery. Recovery of value-added products has led to cost reduction, conservation of energy, environmental sustainability, and customer service improvement (Hernández-Sancho et al., 2010).

Apart from microalgae technologies, one of the common techniques in recovering VAPs is anaerobic digestion, a process where microorganism feeds on organic materials to produce biogas (Edwards et al., 2015). Biogas is known to contain carbon dioxide, water vapour, and 50% methane (Yi et al., 2019). This process occurs in closed spaces where oxygen is unavailable and collected effluents are handled to pretreat the organic materials and adjust the total solid content. It then enters the covered anaerobic digester where microorganisms digest materials such as fats, oil, food scraps, animal manure, and grease to a renewable energy, biogas. This technique is a net energy-producing process that benefits economically and environmentally. It sanitizes feedstock put through it and converts it to fertilizers, reduces odour, and has a low capital cost. However, there are also drawbacks to it, such as maintenance of operation is required, and a large-scale process needs to be repeated to convert it into biogas efficiently. Another method used in the recovery process is the hydrothermal processes, which is a more advanced technique. Sludge containing biowaste is dehydrogenized, which is a chemical reaction to remove hydrogen, then it would decompose and degrade to release gas, produce oil, and stable solids. These sturdy solids are left to separate from moisture, which is relatively remained as liquids to avoid latent heat consumption (Xue et al., 2015).

The need for recovering VAPs is the production of biogas which is used as renewable energy. This replaces the power of burning fossil fuels which produces greenhouse gases that cause global warming which increases the temperature of the earth (Umair Shahzad, 2017). Energy used from methane is another method to reduce the cost of electricity due to the high power supply by small amount; hence, it benefits many industries for future prospects (Sonich-Mullin, 2014). This review focuses on a more commercially effective method, which is known as microalgae harvesting. A new emphasis on biorefinery has been motivated by the interest in microalgae as a renewable and sustainable feedstock for biofuel production.

2. Benefits of microalgae cultivation

2.1. Recovery of value-added products from wastewater

Microalgae have attracted interest in commercial production due to its potential in providing biofuels. Several studies have shown the feasibility of microalgae as an advanced wastewater treatment due to its high efficiency in extracting contaminants from domestic, industrial, and agriculture wastewaters (Acién Fernández et al., 2018). Microalgae can grow well in wastewaters as it could take advantage of the high amount of nitrogen and phosphorus present as well as carbon dioxide, ultraviolet light, and other organic matters as a carbon source. The four main components of microalgae are proteins, carbohydrates, lipids, and nucleic acid (Roy and Pal, 2015). Nutrient's content varies with their sources which greatly affect microalgae growth and lipid content. The rise in the urban population has equally increased municipal sewage. Municipal wastewater has low nitrogen and phosphorus content compared to other wastewater but heavy metals such as lead, and zinc are often found (Tjandraatmadja et al., 2010). Municipal wastewater is also classified as raw sewage, secondary effluent, and centrate which is a by-product of sludge. Centrate is a nutrient-rich effluent, contains the highest nitrogen, phosphorus, and COD value compared to others which are approximately around 124.2, 208.3, 2320 mg/L, respectively (Li et al., 2019) as shown in Table 1.

Agriculture wastewater is mainly produced from livestock production which is one of the main sources of wastewater (Cai et al., 2013). Animal waste from cattle, swine, and poultry generally have high nutrient values that are important to recover as fertilizers. Animal waste cannot be directly treated with microalgae due to the presence of suspended solids, and exorbitant ammonium concentration; hence, anaerobic digestion is conducted initially. Diluted wastewater is commonly reliable for nutrients recovery by autotrophic algae species (Puyol et al., 2017). Industrial wastewater contains relatively low nitrogen and phosphorus content but high metal content.

Microalgae are photoautotrophic microorganisms that use solar energy and carbon dioxide as energy and carbon source to reduce inorganic nutrients such as nitrogen and phosphorus to organic matter thus producing biomass (Muhammad et al., 2020). A consortium of microalgae and bacteria is what usually exists when we are utilizing microalgae for wastewater treatment. While consuming oxygen bacteria oxidize the organic matter to inorganic materials, whereas microalgae take up the inorganic compound to produce biomass and release oxygen with the help of light. The consortium in this process can differ depending on the condition in the reactor; hence, it is seen that composition of the consortium determines the oxygen production, carbon dioxide consumption as well as nitrogen and phosphorus fixation. Algae can reduce carbon dioxide by 513 tons and generate up to 100 tons of dry biomass annually per hectare and this could further produce biodiesel and hydrogen (Molazadeh et al., 2019). The bio-fixation of microalgae-derived carbon dioxide can encourage valuable algal biomass production and reduce greenhouse gas emissions simultaneously. Microalgae have been confirmed to have the ability to collect sunlight and use that energy to store carbon during the photosynthesis process. Microalgae generates oxygen during the growth phase, and they produce fatty acids and carbonates. Once the biomass has reached an optimal growth rate, it can be extracted for the production of bio-fuels, bioenergy, and food additives (Acién Fernández et al., 2018).

Microalgae are fit for wastewater treatment due to its high growth rate in different environments with its low cost in assimilating pollutants, efficiently recover nutrients which will meet the desired or required standards and produce biomass which will replace energy generated from fossil fuels. Microalgae do not compete with other crops for land, and it can use up carbon dioxide which is considered as a greenhouse gas which becomes an environmentally friendly alternative. To improve biomass production from microalgae, balancing carbon to nitrogen ration is also one of the effective ways (Zheng et al., 2018). At

Table 1
Content of various wastewater sources.

Sources	Description	COD (mg/L)	TN (mg/L)	TP (mg/L)	N/P	Reference(s)
Municipal wastewater	Raw sewage	231.0	40.65	5.66	7.18	(Kong et al., 2021)
	Secondary effluentCentrate	42.2	44.2	1.61	27.45	
	(sludge by-product)	2320	124.2	208.3	0.59	
Agriculture wastewater	Dairy manure	38230	3305	266.0	12.42	(Dai et al., 2015; Khoufi et al., 2015)
	Poultry manure	7306.4	1313.5	248.0	5.30	
	Swine manure	12152	3304	192	17.21	
Industrial wastewater	Textile waste (liquid effluent)	200	39	5.35	7.30	(Freitas et al., 2015; Yurtsever et al., 2015)
	Brewery waste	3638.5	244.5	25	9.78	

COD- chemical oxygen demand, TN- total nitrogen, TP- total phosphorus.

least there are 3000 known microalgae species that are cultivated to extract high-value products such as pigments and proteins (Loekas-Soesanto, 2016).

Microalgae-based treatment technologies have a number of benefits, including a high rate of growth and effective biogenic element sequestration (Sivakumar et al., 2012). Furthermore, microalgae provide photosynthetic aeration, with photosynthetically evolving oxygen readily oxidizing organic molecules and promoting the growth of heterotrophic bacteria that consume organic wastes (Randrianarison and Ashraf, 2017). Additional advantages of this biotechnology include reduced electric energy consumption due to reduced aeration and mechanical mixing requirements. Microalgae biomass grown in wastewater is high in lipids and carbohydrates, and it can be transformed to biofuels like biodiesel, biogas (methane), and biohydrogen (Solovchenko et al., 2013).

2.2. *Production of biofuels as a renewable energy*

Microalgae-based process involves pre-treatment which carries out filtration to remove suspended solids, bioreactors which recovers nutrients and produces biomass, harvesting biomass and finally the transformation of biomass into bioproducts (Rajkumar et al., 2014). Microalgae cells are small, similar density to water and their concentration is from 0.5 to 0.3 g/L which is rather low; hence, harvesting of microalgae to recover biomass is crucial and could be considered a challenge (Drexler and Yeh, 2014). Harvesting can be carried out through a low-cost preconcentration of the biomass and next by drying the harvested algae biomass to reach about 100 g/L (Udom et al., 2013). Sedimentation and flotation are influenced by coagulants/ flocculants that alter the physical properties of microalgal biomass which is an ideal way for a low energy consuming technology. Certain microalgae species with its biomass productivity is shown in Table 2.

Energy demand has increased since the number of populations increased which demands a constant supply of energy such as electricity. Renewable energy has become a priority nowadays due to its environmental benefits such as reducing greenhouse emissions for a sustainable future and enhance energy security (Ozturk, 2014). Harvested microalgae biomass are converted to biofuels such as biodiesel, this could be achieved due to the high lipid content it holds. It contains no more than 30% of the total biomass needed for developing biorefinery schemes which can process and use the remaining 70% of the biomass. The best option is to produce biogas which utilizes 65% of the total biomass while if it is transformed into biodiesel than it only needs 30% of the biomass (Vanthoor-Koopmans et al., 2013). On the other, 40% of the biomass can be transformed into bioethanol (Kahr et al., 2013).

There is a need for carbon sequestration approaches and renewable fuels in the light of climate change and rising energy demand (Peter et al., 2021). This can be accomplished by cultivating microalgae, a microscopic unicellular alga that transforms carbon dioxide into high-value bioproducts and energy. Biogas is produced by anaerobic digestion and it could be modified to another useful biofuel known as biomethane (Moreira et al., 2019). Biomass slurry enters the anaerobic digester which goes through hydrolysis that breaks down macromolecules into simpler compounds and this process is essential as it determines the efficiency of methane produced. The hydrolysed molecules enter acidogenesis, and acetogenesis which then undergoes methanogenesis to produce biogas. When producing ammonia, hydrogen, carbon dioxide, hydrogen sulphide, shorter volatile fatty acids, carbonic acids, alcohols, and trace quantities of other by-products, these fermentative bacteria create an acidic atmosphere in the digestive tank. As carbon dioxide and trace gases are extracted from biogas, biomethane is left as a methane-rich clean natural gas substitute (Teng et al., 2014). Biomethane may be used as a vehicle fuel, pumped into the gas grid, or used to generate both heat and electricity.

Pre-treatment of microalgae to alter its cell wall structure and composition requires a lot of energy; hence, improvement with an efficient and economic performance with further research may boost microalgae biogas production. More than 200 L of biomethane can be produced per kg of microalgae biomass which could be used as vehicle fuels, electricity to powerhouses and industries, replacement of on-site diesel usage, and for the removal of carbon dioxide (Thorsten Ahren, 2014).

Biodiesel is produced from harvested biomass by extracting its lipids. Hexane which is a non-polar organic solvent is penetrated to the cytoplasm of the algal cell, this will interact with neutral lipids forming solvent-lipids complex (Mata et al., 2010). An organic solvent lipid known as oil is eventually formed due to Van der Waals forces and hydrogen bonds. Lipids recovered contains 90% triglycerides and undergoes transesterification which produces biodiesel (Mostafa El-Sheekh, 2017). Algae that are commonly used to produce biodiesel are

Table 2
Biomass productivity and components from several microalgae.

Microalgae Species	Treatment sources	Carbohydrate (%)	Protein (%)	Lipid productivity	Biomass productivity (mg/L d)	Reference(s)
Scenedesmus obliquus	Secondary effluent	13.5	53.0	7.95	39	(Gupta et al., 2016)
Chlamydomonas reinhardtii	Centrate (sludge by-product)	17.0	48.0	320.5	1410	(Li et al., 2019)
Chlorella spirulina	Digested dairy manure	14.5	54.5	9.05	126	(Shi et al., 2016)
Chlorella vulgaris	Digested piggery	13.0	54.5	25.6	10	(Li et al., 2019; Sun et al., 2019)
Chlorella pyrenoidas	Soybean waste	26.0	58.7	40.0	525	(Hongyang et al., 2011)
Spirulina platensis	Digested starch	16.5	49.8	–	2180	(Zhang et al., 2015)

Chlorella protothecoides which generates 55.2% of biodiesel, *Botryococcus braunii* which generates 17.85 of biodiesel, and *Cladophora fracta* which generate 8.2% of biodiesel (Kothari et al., 2017). Markets are raising awareness on the benefits of biodiesel not only it is renewable energy and it provides economic benefits due to its replacement on burning fossil fuels (Moriarty et al., 2017).

Microalgae biomass is used to produce third-generation bioethanol by several processes such as pre-treatment for cell rupture, to make available carbohydrates, proteins, lipids, and value and compounds, and to modify the structure of an intercellular carbohydrate (de Farias Silva and Bertucco, 2019). Pre-treated microalgae cells enter hydrothermal treatment to break down the cell wall and to gelatinize intercellular starch (Velazquez-Lucio et al., 2018). It is then fermented to produce bioethanol. Algae such as *Chlamydomonas reinhardtii* produces 60% bioethanol, *palmaria* produces 56% bioethanol, and *Chlorococcum sp*. produces 26% of bioethanol (Kothari et al., 2017). Bioethanol is a flammable colourless liquid with high octane and is commonly used as a motor fuel (Magdalena Zabochnicka, 2014). Biohydrogen which is derived from algae such as *Gloeocapsa alpicola* is also used as an automotive fuel.

Biofuels are like investments for a better future since their feedstocks are recovered from waste; hence, this shows that it is cost-efficient. It also provides economic security especially for countries that depend on the import energy supply (Datta et al., 2019). In 2019, China imports approximately 768.94 million metric tons of fossil fuels, India's import of fuels expanded by 3.8%, and North Korea was ranked number 5 (Alvera, 2020). These countries depend on third countries such as Germany to export energy; hence, an alternative solution must be determined to achieve energy security. Such countries that import fossil fuels have huge potential in producing biomass with technologies utilizing microalgae due to the population size and availability of sources which reduces import costs and the use of fossil fuels in replace to renewable energy. The world's fuel supply will be made up of biofuels, which will rise to 30% in the mid-century today. European union produces 42% of its energy while 55% is imported from third countries. European Commission has proposed the use of bioenergy and to produce 20% of energy by 2020 (Scarlat et al., 2015). In comparison with other renewable energy sources, the number of countries using energy from biomass has rapidly increased and has helped make biomass an attractive and promising alternative. The capacity to manufacture oil throughout the year is thus higher with microalgae than the most effective oil plants (Gendy and El-Temtamy, 2013).

2.3. Commercial application of value-added products

Nitrogen and phosphorus is a useful high value product that can be recovered from waste to be used for various application especially in agro-industrial sectors (Mehta et al., 2015). Several methods are used to obtain nitrogen such as electro dialysis which involves stripping and adsorption into an acid solution (Perera et al., 2019). Microalgae are able to obtain organic nitrogen by converting existing inorganic nitrogen using the process called assimilation and its fixation are helped by cyanobacteria within the intercellular fluid (Jia et al., 2016). Moreover, inorganic phosphate such as dihydrogen phosphate which was readily found in industrial wastewater is transformed into organic phosphate by phosphorylation using microalgae to be utilized further in fertilizer mixture (Sengupta et al., 2015).

Nitrogen and phosphorus which are essentials to make up chlorophyll, amino acids and cell growth are used as fertilizers which are used for the growth and increase the productivity of the crops (Theregowda et al., 2019). Bio fertilizers is one of the common commercial products from recovered value-added products which are also on-demand as it does not pollute or contaminate soils as chemical fertilizers do. The quality of microalgae-based bio fertilizers primarily depends on the downstream processing of the microalgae and its efficiency. Fertilizers are easy to transport, easy to apply due to its ability to dissolve in soils and, amounts could be predicted according to its requirement. Microalgae could further enrich fertilizers due to the presence of micronutrients such as magnesium and iron which are commonly missing in artificial fertilizers that causes depletion to soils (Fernandes et al., 2017).

Microalgae biofertilizer can produce plant growth hormones, polysaccharides, antimicrobial compounds, and other metabolites to promote plant growth in addition to improving soil fertility and quality. Sustainable agriculture has an advantage over traditional agriculture in that it can meet food demand while using natural resources without harming the ecosystem (Chatterjee et al., 2017). Environmental stress is becoming a major issue, and productivity is dropping at an alarming pace. Our reliance on chemical fertilizers and pesticides has aided the growth of industries that produce life-threatening chemicals that are not only harmful to human health but also have the potential to disrupt the ecological balance (Mącik et al., 2020). Biofertilizers will assist in solving the problem of feeding an ever-increasing global population at a time when agriculture is under pressure from a variety of environmental factors (Bhardwaj et al., 2014).

Another commercial application of value-added products recovered is to produce health supplements. *Haematococcus pluvialis* is the main source for astaxanthin which is a reddish pigment used to treat Alzheimer's disease, stroke, and liver diseases (Dhankhar et al., 2012). UV exposure strongly causes pigments, skin discoloration, and immunosuppression and contributes to photo aging acceleration. astaxanthin is an important compound in the field of dermatology because of its role in diverse biological activities (Davinelli et al., 2018). Moreover, algal components are commonly employed as thickening agents, water-binding agents, and antioxidants in cosmetics. *Arthrospira* and *Chlorella* are two of the most common microalgal species found in skin care products (Náthia-Neves et al., 2018).

Microalgae have long been recognized as a valuable renewable source of bioactive lipids with a high concentration of polyunsaturated fatty acids (PUFA). Pigments are useful as natural colours, and polyunsaturated fatty acid oils are added to infant formulae and nutritional supplements (Barkia et al., 2019). Incorporating microalgae into animal feeding improves its health due to the nutrient microalgae provides such as proteins, carbohydrates, lipids, and vitamins. Algal biomass should be high in digestible protein and long-chain omega-3 fatty acids, which can supplement fishmeal and fish oils, for animal feed (Benemann, 2013).

3. Recovery of high value-added products

3.1. Value-added products recovery from industrial wastewater

Industrial wastewater is the residual water used after manufacturing commercial products such as food industries, textile, rubber industries, cement industries, oil and mining, and chemical industries. Industrial wastewater also accounts for around 22% of global wastewater according to the United Nations World Water Development Report (Stewart, 2020). Industrial water is known to contain many organic and inorganic nutrients as well as toxic materials which is the reason that regulations about the quality of wastewater are determined before it is discharged to the environment. The colour of the wastewater is generally light grey but if it has undergone anaerobic decomposition then the colour will be much darker due to the presence of sulphides while the temperature of water depends on the season and it has to be maintained during treatment for biological processes (Alturkmani, 2013).

Steam electrical generating plants discharge wastewater with high temperatures from the condenser cooling water (Raptis et al., 2017). This heat distributed could cause ecological harm such as death of aquatic organisms due to shock in change of temperature and decreases resistance to diseases and toxic metals. Therefore, it is necessary to treat the water before releasing to the environment and optimizing it to the required conditions and quality. In order to do so, microalgae growth is utilized in recovering value-added products from this wastewater. For large-scale microalgae cultivation, open ponds and enclosed photobioreactors are currently used, and various harvesting technologies are being established to achieve as low-cost microalgae capture as possible (Tan et al., 2020).

Most solid waste and wastewater is released into the soil and water systems, thereby posing a significant threat to the ecosystem's regular functioning; hence, it needs to be treated (Ferronato and Torretta, 2019). On the other hand, excessive nutrients can lead to algal blooms, oxygen deficits and an increase in colour and turbidity in the receiving of water (Wurtsbaugh et al., 2019). Filter press is one of the common methods to deal with this wastewater as it is more effective to deal with the precious waste it contains (Stickland et al., 2018).

3.2. Recovery techniques and technologies for value-added products

Nitrogen and phosphorus are major nutrients that are released by most agriculture industries and it holds up the potential for further applications by recovery using developed technologies. Ion exchange is a method for this recovery where its cation resin contains strong acid and the anion resin contains a weak base. The wastewater is first treated with a sand filter and then is diluted before entering the regeneration vessel. Product from fertilizer wastewater is an ammonium nitrate solution and this can be reused again as a fertilizer. Ion exchange also contributes to the chemical production of ion resins and the pollutants recovered are of that required (Lito et al., 2012). Adsorbents for the cation exchange might also be used for the recovery of potassium. Adsorbents suitable for removing resources or pollutants of interest can be selected and combined (Tarpeh et al., 2017). While these processes for ion exchange seem promising, frequent regenerations with new chemical solutions and high waste disposal costs are long-term non-economical (Huang et al., 2020).

Ammonia stripping is an air-connected wastewater method for the removal of ammonia gas from wastewater (Ahmed Alengebawy, 2019). The stripping of ammonia in conjunction with anaerobic digestion appeared to improve anaerobic digestion in effectively extracting ammonia and toxic compounds (Kinidi et al., 2018). The inorganic fractions of phosphorus have increased in anaerobic digestion and chemical precipitation with magnesium and iron is utilized (Carrillo et al., 2020). Fruit and beverages industries have useful nutrients such as phenolic compounds, organic acids, and pectin that are recovered by either aerobic or anaerobic digestion. Moreover, palm oil effluent includes nutrients such as carotene, protein, and carbohydrate that are regenerated by membrane process (Chen et al., 2019).

On the other hand, the use of intensively cultivated phototrophic microorganisms, microalgae, as a modern method of biological treatment and conversion of agriculture waste is further reviewed. The most promising microalgae strains have a fast growth rate, which is necessary for efficient nutrient removal (Yu et al., 2019). Microalgae produce dissolved oxygen, which rapidly oxidizes organic pollutant substances. Incubation of suspended or immobilized MA cells in wastewater has been shown in numerous studies to be a very promising method for final (tertiary) stage treatment (Solovchenko et al., 2013).

Carotenoids are regarded as the most important food antioxidants and its importance for human health in medicine has attracted markets to recover it from waste (Mezzomo and Ferreira, 2016). Food slurry from fruits and vegetables contain carotenoids of different sorts that can be biotechnologically produced such as β-carotene by the fungus *Blakeslea trispora*, and astaxanthin which has high vitamin E content and produced by the freshwater microalga *Haematococcus* sp. Culturing of algae and on the microorganisms where it is coagulated and then precipitated is one of the most efficient methods in recovering. Freezing and ultrasonic cycles followed by chemical treatment with dimethylsulfoxide and combining of enzymes is a method to recover carotenoids as well.

Starch processing water from potato manufacturing industry is known to have a high content of protein where foam separation and membrane technology by ultrafiltration is used for its recovery (Dabestani et al., 2017). High yields of concentrated protein are achieved by inclined foam separation, sedimentation, centrifugation, and ultrafiltration. These treatments remove starch and fiber while increasing the purity of protein recovered. The ultrafiltration system has a membrane with a molecular weight cut-off of relatively 30,000 to 50,000 Da. The proteins recovered are further used to make essentials enzymes. The use of enzymes in an aqueous medium enables oil separation from protein and pseudomembranous that surround the oil systems by hydrolysis. There are three different fractions during enzyme-assisted aqueous extraction of soybeans such as an emulsified oil cream, a protein, and a sugar-rich skim, and a residual fiber-rich one. Protein is obtained by skimming it off (Zhang et al., 2019b).

The recovery of proteins from microalgae is gaining attention for animal feed applications, especially for fish feed, since aquaculture feeds account for 40 to 70% of the cost of the fish raised. Furthermore, using pig manure to generate microalgal biomass may help with manure bioremediation, reducing the environmental effect of storage. In order to completely apply the biorefinery principle to valorise the resulting biomass, the methane capacity of the by-products obtained after protein recovery was also measured for future prospects (Hernández et al., 2018).

3.3. Transformation of value-added products into bio-products

The development of plastic has exceeded any other commodity due to its flexibility and durability. Most of these plastics tend to be used only once, which leads to a single use set of disposable plastics. 270 million tons of plastic are produced globally in 2010 while plastic waste exceeds this production value for around 275 million tons (Eriksen et al., 2014). Leakage to the environment is due to the improper plastic waste management and of 0.24 million tons of plastic waste entering the ocean (Schmaltz et al., 2020). In the plastics industry, Malaysia is a global player with approximately 1,300 plastic producers. By 2016, Malaysia's exports were RM30 billion, which accounted for 2.26 million tons of resin used for plastic processing. About 0.94 million tons, of which 0,14 to 0,37 million tons may have been washed into the ocean due to the mismanagement by manufacturers in Malaysia (Patra, 2014). The top countries that contributed to Malaysia's import of plastic waste are China, United States, Japan, United Kingdom, Germany, and Australia (Behzad et al., 2011). These plastics take a long time to degrade; hence, it is disposed to landfills which takes up a lot of space, build-up diseases, and is an unpleasant sight for the society. Plastics that enter the ocean could be mistaken for jellyfish by animals such as turtle which causes intestinal blockage and eventually die due to starvation. An alternative approach is needed to reduce plastic waste pollution by converting value-added products from wastes to bio-products that are environmentally and economically sustainable.

The potential stems benefits of microalgae are high productivity, output potential all year round, cultivation for non-arable land, use of polluted and saltwater supplies, and waste stream integration (Beckstrom, 2018). Microalgae biomass can be a potentially improved to form bio-plastic source as it do not compete with food, can grow on waste capital, and can achieve high accumulation of lipids. Microalgae bioplastic production can be more reliable and supports the circular economy such as food packaging, pharmaceuticals, and cosmetic industries (Cinar, 2020). Bioplastics are formed by combining microalgae biomass, bio-petroleum based polymers, and additives through thermal–mechanical methods. Chlorella is a green alga where blending with additives is important to produce bioplastics. Pre-treatment using ultrasonic homogenization can enhance the homogeneity and surface characteristics of Chlorella-PVA mixtures, which are an alternate in food packaging. Spirulina is known for its ability to the adaptation to a harsh environment in the food industry as a protein source for many years and has the potential to produce bioplastics (Cinar, 2020).

Polyhydroxyalkanoates are derived from either wild strains or recombinant strains that can accumulate large concentrations of polymers from pure microbial crops. Polyhydroxyalkanoates are derived from either wild strains or recombinant strains that can accumulate large concentrations of polymers from pure microbial crops. It is grown in sealed reactors in controlled conditions where the process parameters are stable and sterile. The strict conditions include high operating costs, almost 11% of the total cost of output because of media sterilization and reactor maintenance (Fra-Vazquez, 2020). The other approach is based intracellularly in microalgae cells of biopolymers such as polyhydroxybutyrates and starch. The efficiency of the development of poly-β-hydroxyl butyrate from a high-quality algal pond with microalgal biomass will lower operating costs and make it an attractive prospect for many manufacturing, therapeutic and diagnostic applications (Abdo and Ali, 2019). Food waste has high moisture content and when mix with a bulking agent with high carbon to nitrogen ratio it will absorb the excess moisture (Palaniveloo et al., 2020). This food slurry can be used as a bio-compost where leachate is reduced through sufficient aeration. This reduces solid waste disposal from municipal wastes while reducing landfill space, it recovers valuable raw ingredients, it protects groundwater quality, reduces methane emission, and becomes a long-term fertilizer (Parchami et al., 2020).

3.4. *Challenges faced throughout the recovery process*

If an industrial waste stream is released into an unmanaged waste treatment system, the discharge may cause serious problems. Unmanaged waste due to the poor development of treatment may cause violation of the discharge regulations which may lead to the prevention of reuse water. Industrial wastewater contains dissolved metal salts that lead to a ranging pH value of between 6 and 9 (Soliman and Moustafa, 2020). Depending on the existence of the ions, some values of pH-solution achieve precipitation of heavy metals from wastewater. These behaviours demonstrate that in a multi-stage phase, the heavy metals must be neutralized and separated and that an automatic control system must be used for each stage (Rabii et al., 2019). pH control to stabilize the wastewater could be done by adding carbon dioxide (Abashar, 2014). The presence of heavy metals are at higher concentrations in industrial wastewater as it is associated with the solid part of presence in wastewater due to their hydrophobic nature (Tiruneh et al., 2014).

Wastewater containing high concentrations of heavy metals means it is polluted and causes the number of microorganisms to decrease substantially. Heavy metals are altered by changing cell density and species resources in the activated sludge microorganism structure. As heavy metal content rises in wastewater, microbes become toxic as heavy metal binds and create complication with it (Sa'idi, 2010). The performance and protection of these processes, together with the overall costs, are limited by heavy metals and other pollutants such as polycyclic aromatic hydrocarbons, dioxins, and furans (Raheem et al., 2018). Dumping and spillage that occur at times may have negative effects on the performance of the wastewater treatment plant. Complication on biological oxygen demand value as a determination of total dissolved oxygen could occur in spillage of wastewater that causes diversity in its value. This also applies to chemical oxygen demand value which is known to be less specific than biological oxygen demand value (Water Research Commission, 2016).

The availability and cost of carrier content is one of the major challenges in carrier-based algae formulations. Using agricultural, agro-industrial, and animal wastes may be a cost-effective and useful option; however, degrading lignocellulosic agricultural and agro-industrial wastes is a significant challenge. The use of algae biofertilizers and their benefits is becoming more widely recognized, and there is a large market opportunity for them. However, the challenges of commercialization must be addressed through large-scale field studies and the advancement of cost-effective fertilizer production technologies (Renuka et al., 2018).

4. Potential source for the production of value-added products

4.1. *Leachate treatment via microalgae*

Domestic solid wastes are regarded as the substances resulting from human activities that are required to be treated in order to be disposed of safely (Abdel-Shafy and Mansour, 2018). These solid wastes consist of daily products such as bottles, food scraps, and plastic containers (Adipah and Kwame, 2018). These wastes are generally disposed of as dry wastes known as garbage. Organic solvents when is released to the environment without following the proper guidelines may cause bioaccumulation in the food and could be toxic such as a film of oil or grease on the lining of water that unable oxygen from dissolving (Abdellah, 2013).

The global generation of solid waste is expected to rise. Landfilling is now the most widely used form of solid waste disposal. However, over time, these landfill sites emit a considerable amount of leachate, which can cause major environmental problems, including water pollution. There are a variety of physicochemical and biological landfill leachate treatment schemes available, all of which have varying degrees of effectiveness. There has been a need for developing eco-friendly, green treatment schemes for landfill leachates with viable resource recovery and minimal environmental footprints as the emphasis on sustainability has increased. Microalgae-based techniques is a good fit for this type of treatment (Nawaz et al., 2020).

Phytoremediation of landfill leachate with microalgae is a promising solution, but complex macromolecular organics and high chromaticity of the leachate inhibit results (Quan et al., 2020). A technique combining ozonisation and microalgae bioremediation was proposed to achieve high-efficiency leachate remediation and microalgae biomass processing. The leachate was first pre-treated with ozone to degrade most macromolecular organics and minimize chromaticity.

It was discovered that cultivating a microalgae consortium was feasible, with increased biomass productivity (Barreiro-Vescovo et al., 2020). The dark colour of the digestate, along with its high content of suspended solids, necessitated pre-treatment of the liquid and field dilution. The light penetrability and nutrient availability were both affected by the pre-treatment process, which had a significant impact on reactor efficiency. In terms of nutrient removal, heavy competition with nitrifiers lowered nitrogen removal quality. This argument should be explicitly discussed in future research with the aim of slowing down the nitrification process and increasing nitrogen utilization by microalgae.

4.2. *Domestic waste sludge*

The incorporation of energy production and the conservation of resources in the production of clean water in microbial biotechnology is important for developing a circular wastewater economy (Nielsen, 2017). If microbial consumers are unable to recover and recycle essential nutrients, then a sustainable life for organisms cannot be achieved (Awanish Kumar, 2017). Microalgae are promising biological systems that handle range wastewater sources as well as domestic solid sludge due to its metabolic versatility (Puyol et al., 2017). Direct absorption of water pollutants and improving purification efficiency by providing oxygen which also reduces the direct addition of oxygen supply are the two main purposes of microalgae.

Typically, municipal waste treatments are performed outdoors under physiological temperature and pH (Wollmann et al., 2019). Therefore, the degradation of water impurities at the point of origin is important for micro specialists who are sensitive to heating, psychrophilic, and acidophilic environmental conditions. *Galderia sulphuria* is an example of microalgae species that is cultured on a 700 L open space with a mixotrophic growth condition that produces biomass at a removal rate after 3 days (Wollmann et al., 2019). This microalgae species is able to acidify the environment which reduces the cost of pH control.

The pond system is applied as a large-scale reactor of microalgae cultivation due to its easy construction and low cost of investments. However, the capacity of light entering such a system is low; hence, paddle wheels and supply of important gases are installed for efficient algal biomass production. The immobilization of microalgae provides an excellent approach to the achievement of metabolic conversion and efficient harvesting of biomass. These microalgae technologies have been put into practice by several countries. Australia uses photosynthetically active radiation in a closed photo-bioreactor system where the biomass produced is digested to further produce an alternative biofuel such as biogas (Medipally et al., 2015). Moreover, microalgae, which produce substantial volumes of biomass and oil, can be utilised as a feedstock for biodiesel synthesis and has been considered as a possible source of renewable energy. Additionally, microalgal biomass can be used to produce biohydrogen via anaerobic digestion, biogas, bioethanol, bio-methanol, bio-plastics, bio-fertilizer, therapeutic value products, and animal feed (Catone et al., 2021). Thus, making use of waste, residual flows, and recycling of these nutrients can result in significant cost savings for nutrient supplementation in producing high yield microalgae biomass.

Domestic sewage sludge has become the biggest solid waste in Malaysia overloading landfill sites and it is known that solid waste production is increasing at 15% per year (Abd Kadir et al., 2013). Bacillus thuringiensis is a very well-known biological agent that possesses the ability to achieve the inclusion of protein parasporal crystal during δ-endotoxin sporulation, this is used as biopesticides as well as in the health sector (Chandler et al., 2011). Sewage sludge undergoes a fermentation process where pH, carbon to nitrogen ratio, dissolved oxygen concentration, solid concentration, and sludge type are several factors that need to be kept under consideration. Aeration is necessary during fermentation to optimize the development of cell growth, sporulation, and δ-endotoxin production which, according to its solid contents, can also cause extreme foaming. Sludge is also dewatered by belt filter press which then is transferred for harvesting and eventually formulates the product (Zhuang et al., 2011). Biopesticides are useful to kill pests or insects by causing lysis on their gut cells, which does not have harmful residues, easily decomposed or biodegradable, and it has a long-term effect. However, it is known to have a slower activity rate than chemical pesticides which may cause economical loss (Loekas-Soesanto, 2016).

Environmentally friendly bio-flocculants that are non-toxic and are easily degraded are secreted by microorganisms that make use of activated sewage sludge. Bio-flocculants are effective, efficient, stable, and are chosen over chemical flocculants due to the health problems and pollution that it may cause. Moreover, bio-flocculants have attracted attention due to its potential to reduce environmental pollution. Polysaccharides, proteins, and cellulose are macromolecule contained in sewage sludge that is also the source of bio-flocculants. Saccharomyces cerevisiae is cultured under waste active sludge fermentation to produce bio-flocculants (Yan et al., 2020b).

Microorganisms release surface-activating bio-surfactants to emulsify, at the expense of water-insoluble substrates of organic carbon substrates during development. It has been demonstrated that cell lysis can be extracted directly by alkaline treatment and subsequent biosurfactant release by domestic active sludge (Alvarez-Gaitan et al., 2018). However, the pathogenicity of some commonly found microbes in municipal waste may influence its practicality. Furthermore, another product coming from sewage sludge are enzymes which are recovered efficiently without disrupting its enzymatic activity by ultrasonication or ion exchange resins (Plattes et al., 2017).

4.3. *Food industrial waste slurry*

Municipal food waste must be separated from other waste and mostly it comes in the form of solid wastes. Household sectors in Malaysia produce 44.5% of food waste which becomes a great concern as well for the solid waste management department as food waste deposited into landfills may cause emission of greenhouse gases. The landfill is known to be the main source of 47% methane emission which causes ozone depletion which eventually causes global warming and it also causes the spreading of unpleasant odour into the atmosphere (Zhang et al., 2019a). Food slurry waste needs to be maintained and valuable products need to be recovered to decrease the spreading of diseases that may affect human health and to save the cost of landfill maintenance. Food waste in Malaysia is commonly generated in urban areas, restaurants, and the food and beverage sector. However, fruits and vegetables are readily available for composting while meat and dairy products are much harder to compost. For example, organic fruit and vegetable wastes from a market in Kuching are used for composting to contribute to a project (Sonia Heaven, 2018). Food waste trapped during filtration in a treatment plant is shredded and ground into smaller pieces, biological agents such as enzymes and microorganisms are added on top of freshwater. Food waste enters an aeration tank where it is degraded with the help of a paddle and oxygen gas. The slurry is then deposited on the bottom of the tank where it is then removed. This food waste slurry contains a bioactive compound that has great potential to be refined and restored to develop value-added products and reduce environmental impacts (Náthia-Neves et al., 2018).

Anaerobic digestion is contingent on the interaction between microorganisms that are able to conduct the four stages such as hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Anukam et al., 2019). The hydrolysis process helps to convert organic macromolecules into smaller components that can be used by acidogenic bacteria. Extracellular bacteria can be released by hydrolytic bacteria to convert carbohydrates to sugar, lipids to fatty acids, and proteins to amino acids. The smaller molecules are then released by the enzymatic cleavage which in turn can diffuse through the cell membranes. Carbohydrates such as lignin, cellulose, and hemicellulose are difficult to recover due to their complex structure; hence, extra enzymes are added (Meegoda et al., 2018). Acidogenesis occur in a very rapid condition that produces volatile fatty acids which creates a forerunner for the final stage (Parchami et al., 2020). The process of acetogenesis is the conversion of these higher volatile fatty acids and other intermediates into acetate and the synthesis of hydrogen. The lipids undergo an acidogenesis and β-oxidation separate process in which acetate is produced from, and acetate from long-chain fatty acids is formed by β-oxidation (Sikora et al., 2019). Methanogenesis is a process of consuming intermediates to produce methane which is also the final stage of anaerobic digestion. Biomethane, biogas, and volatile fatty acids mark the final product of this digestion. These recovered value-products can be further produced to bioproducts such as bioplastics, butanol, and biodiesels. Consumption in textile industries of acetic, butyric, and propionic acids are used as chemical buildings. Direct use of volatile fatty acids will reduce extra energy-intensive recovery processes and improve economic viability (Chang et al., 2010).

Food slurries are an excellent source for bio-composting as it gives the essential nutrients for the growth of plants and trees. Bio-compost are substances that contain microbes such as mycorrhizal fungi, blue-green algae, and bacteria which increases the fertility of the soil. Bio-compost is an eco-friendly material that does not allow the pathogen to flourish; hence, it improves the soil texture needed for healthy plants to grow (Palaniveloo et al., 2020). Chemical fertilizers are easier to obtain and it has a fast reaction; however, it pollutes the soil and is not very cost-effective. This natural fertilizer destroys harmful substances that may cause diseases to plants which eventually end up in the human system.

5. Challenges and perspectives

Currently, only a few modest and mostly rudimentary microalgae systems are in commercial use. To compete with other methods of generating energy, the techniques and processes used in mass manufacturing of energy products must be progressively refined and upscaled. Cultivation, harvesting, and genetic engineering of microalgae, as well as anaerobic digestion of algal biomass into methane, are among the biotechnical problems that should be reviewed further. Specific microalgae culture is currently restricted to open ponds with extreme conditions such as very high salinity or high pH to inhibit competing algae and zooplankton. Only a few microalgae, such as *Spirulina*, *Chlorella*, and *Dunaliella*, have been successfully grown in open ponds throughout time (ElFar et al., 2021). Despite the effectiveness of open systems, further advancements in microalgal growth may necessitate closed systems because not all algal species of interest grow in highly selective settings.

Centrifugation, flocculation using alum, ferric chloride, or chitosan, and hydrophobic absorbents or adsorbents are commonly used in microalgae production for high-value products (Barkia et al., 2019). However, these technologies have substantial costs and energy needs for harvesting algal biomass. For the advancement of harvesting techniques, various approaches are available. The settling of algae by forced flocculation is a low-energy technique. Another biotechnical problem is extracting lipids from microalgae since the oil is difficult to get due to the thick cell wall.

Energy is used to grow and process microalgae, both in terms of infrastructure and operation. The energy inputs of microalgae production can exceed the energetic output depending on the growth system, harvesting and processing procedure, and yield. Due to the high prices reached for the products, a positive energy balance was not intended in commercial algae cultivation (Ananthi et al., 2021).

6. Future prospect

It is understood that wastewater contains essential nutrients that could be recovered and reused to build multiple applications. Nowadays, extraction technologies have expanded; however, some factors need to be overcome to achieve sustainability. Sewage sludge is now a rising waste source that is both expensive to handle due to its operating cost and largely undervalued by its components. To assess the feasibility and to date, several types of research have taken place for any biorefinery production involving waste active sludge. Protein and enzymes extraction are known to be costly due to their small size, which makes it harder, and it utilizes much-modified biotechnology such as ultrafiltration and microfiltration. Further inspection of the operational parameters and non-toxic strains selection is necessary to obtain a progression on the recovery of bioproducts. To enhance performance and economic development, biorefinery research could be conducted on a larger scale instead of in laboratories.

Research focus should strive to incorporate nitrogen, potassium, and phosphorus recovery technologies seamlessly, such as anaerobic digestion and chemical crystallization, and sustainable method of microalgae on full-scale implementation experience. The economic analysis should consider the position of the whole integrated recovered process, as economically feasible routes can differ at state, national, and international levels. Focusing on the reduction in operating cost of nutrients recovery should be another research aim to achieve sustainability. It is anticipated that the production of high nutrition content, low humidity, and low heavy metal and pathogens will increasingly be demanded of end-users by the wide range of relevant technologies (Yan et al., 2020a). The collection of data and routine check-ups on the technologies implanted is encouraged to solve failures and management issues. The improvement of efficiency is an endless process, since numerous alternatives and new technologies are available to extend the life cycle of technologies. The green economy of society will be effectively maintained by micro-algae derived plastics, polymers, high-value chemical compounds, and biofertilizers. For the success of the tremendous production of microalgal biomass, it is important to combine the most advanced biotechnology with industrial development (Chowdury et al., 2020). For better growth and development of biomass, analysis and its monitoring can be further developed into digitalization with cost effective innovation.

7. Conclusion

Microalgae have great potential to grow in industrial effluents, where it can produce high value-added bioproducts. Comparing microalgae harvesting process with other resource recovery methods such as anaerobic digestion and hydrothermal processes, the use of microalgae serves as a more sustainable biotechnology. These value-added products will be converted into biofuels and bioenergy to reduce the reliance on fossil fuels. The overall resource recovery from microalgae contributes to an efficient and sustainable technology. The market value of microalgae-based commodities are expected to expand in the near future and continuous development of microalgae-based processes will be essential.

CRediT authorship contribution statement

Shazia Ali: Writing - original draft. **Angela Paul Peter:** Conceptualization, Writing - review & editing. **Kit Wayne Chew:** Writing - review & editing. **Heli Siti Halimatul Munawaroh:** Validation. **Pau Loke Show:** Supervision, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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