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Bioremediation strategies of palm oil mill effluent and landfill leachate using microalgae cultivation: An approach contributing towards environmental sustainability

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ABSTRACT

Palm oil mill effluent (POME) is defined as the wastewater that contains high concentrations of organics, nutrients and oil and grease generated from the production process of palm oil. Therefore, proper discharge and management of POME is important to avoid deleterious impact on the environment. In fact, solid waste generation is a precursor for its disposal issues as most of the solid waste generated in developing nations is dumped into landfills. This has led to the threat posed by the generation of landfill leachate (LL). LL is a complex dark coloured liquid consisting of organic matter, inorganic substances, trace elements and xenobiotics. Hence, it is essential to effectively treat the landfill leachate before discharging it to avoid contamination of soil, surface & groundwater bodies. Conventional treatment methods comprises of physical, biological and chemical treatment, however, microalgal-based treatment could also be incorporated. Furthermore, with the benefits offered by microalgae in valorisation, the application of microalgae in POME and leachate treatment as well as biofuel production, is considerably viable. This paper provides an acumen of the microalgae-based treatment of POME and LL, integrated with biofuel production in a systematic and critical manner. The pollutants assimilation from wastewater and CO₂ biosequestration are discussed for environmental protection. Cultivation systems for wastewater treatment with simultaneous biomass production and its valorisation, are summarised. The study aims to provide insight to industrial stakeholders on economically viable and environmentally sustainable treatment of wastewaters using microalgae, and eventually contributing to the circular bioeconomy and environmental sustainability.

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1. Introduction

Industrialization, urbanization, and rapid economic growth in Malaysia has resulted in environmental impacts including deple-

tion of nonrenewable resources and environmental pollution. Industrial activities have caused the generation of huge amount of wastewater during the manufacturing process, at daily basis. As Malaysia ranked second as palm oil exporter worldwide, generation of palm oil mill effluent (POME) is one of the biggest concerns to the nation. To acquire every single tons of crude palm oil, about 6 tons of water is used out of which 50% is converted to wastewater or POME [1]. Raw POME contains 0.6%–0.7% oil, 2%–4% suspended solids (SS), 4%–5% total solids (TS), and 95%–96% of water.

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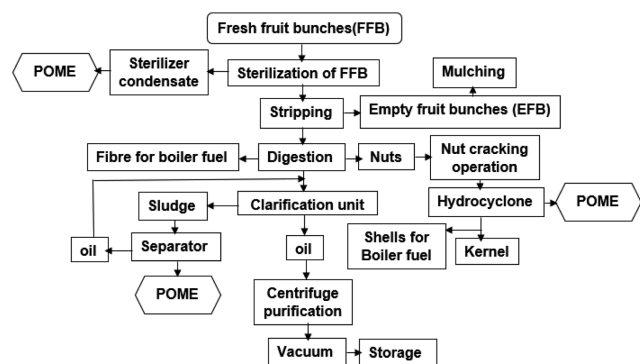


Fig. 1. Palm oil milling process.

Table 1
POME characteristics and discharge standards [7,8].

Parameters	POME (range)	POME (mean)	Discharge standards
pH	3.4–5.2	4.2	5.0–9.0
Temperature	80–90	85	45
BOD	10,250–43,750	25,000	100
COD	15,000–100,000	51,000	400
Suspended solids	5000–54,000	18,000	400
Total volatile solids	9000–72,000	34,000	–
Oil and grease	130–18,000	6000	50
Ammoniacal nitrogen	4–80	35	150
Total nitrogen	180–1400	750	200

The solids are composed of debris obtained from palm fruit mercer, which is generated from (i) hydrocyclone waste, (ii) sterilizer condensate, and (iii) sludge separator. The generation of POME were 0.1 m³, 0.9 m³, and 1.5 m³ from hydrocyclone waste, sterilizer condensate and sludge separator, in sequence, to produce each tonne (1.13 m³) of crude palm oil [2]. The palm oil milling processes are shown in Fig. 1. For the year 2009, it was estimated that Malaysian palm oil mills generated about 44 million m³ of POME in the process of producing 17.5 million tons of crude palm oil [3]. The palm oil industry in Malaysia is therefore one of the major contributors to pollution as it discharges a tremendous amount of POME into water bodies [4].

POME is a non-toxic, but highly odorous liquid waste with very high BOD and COD concentrations [5]. It is reported that most palm oil mills are not abiding to the discharge standards of POME set up by the Department of Environment, Malaysia (DoE), resulting in the subsequent pollution of the associated rivers [6]. The typical compositional concentrations of POME are shown in Table 1 [7,8].

Aside, as the population increased to 33 million in 2022, this is having resulted the increase in solid waste generation as well as landfill leachate (LL) generation. The most common method used for the disposal of solid waste is landfilling [9]. It is a predominant method because of its technically simple nature and advantage in terms of economic perspective over other disposal methods such as composting, recycling and incineration. However, when the percolation of precipitation occurs with the continuous decomposition of organic matter, it results in the formation of complex, dark coloured and odorous wastewater termed as LL [10]. The composition of LL can vary depending upon the landfills age, type of waste, and the climate of the region where the landfill is situated. However, the dominant fraction of LL is composed of organic matter (inclusive of toxic and recalcitrant compounds), heavy metals, xenobiotics, and inorganic substances (sulphate and ammonia *etc.*) [11]. With the amount of rainfall Malaysia has, generation of LL is as well in high quantity. Sanitary landfills with a dumping capacity of 1000 tonnes per day might produce 200–300 tonnes of

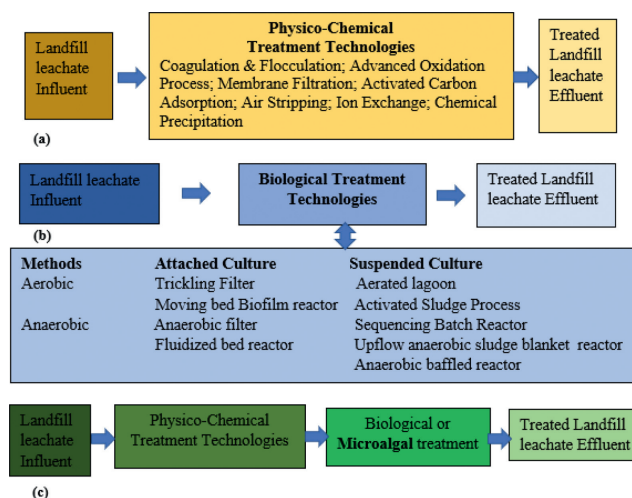


Fig. 2. Landfill leachate treatment systems: (a) Physico-chemical treatment; (b) biological treatment; and (c) combination of physico-chemical with biological treatment.

leachate per day, depending on local meteorological conditions and the moisture level of the solid waste disposed [12]. Therefore, efficient, effective, and environmentally friendly treatment are necessary to ensure safe discharged of treated LL [13,14].

Till date, both wastewaters are still relying on conventional methods to remove the pollutants from wastewaters prior to discharge. The conventional treatment practices include aerobic and anaerobic ponds for the treatment of POME, where the indigenous microbes play the role of bioremediation agents [15]. However, the bottlenecks of using ponds for the treatment of POME are long hydraulic retention time (HRT), large area requirements, and the emission of greenhouse gases [16]. Therefore, nowadays, some millers have modified their facilities of anaerobic ponds to anaerobic digesters to tap the generated biogas and utilize it for generating energy for the mill itself [17,18]. On the other hand, due to the complex, varying and recalcitrant nature of LL, the treatment of LL as well involve combinations of physical, chemical, and biological technologies gave safe and efficient effluent discharge standards. The technologies adopted/employed to treat LL can be mainly categorised into physico-chemical and biological [19]. Physico-chemical treatment technologies are employed when the LL comes from the old landfill and contains recalcitrant refractory compounds. At the same time, biological methods are more efficient if the LL is young [20,21]. Most of the time, no single treatment method is adequate to the extent that the effluent can be discharged safely to the environment. Therefore, a combination of technologies in which physico-chemical treatment methods are integrated with biological methods for better LL treatment [15,22]. Fig. 2 showed the LL treatment systems applied in Malaysia.

The cost used for maintenance and land utilised to build treatment plant are one of the contributing factors on the technologies used for wastewater treatment [23]. This has made researchers to exploit the potential of microalgae in the bioremediation of wastewater, coupled with the recovery of energy and production of other valuable products, so as to overcome the cost incurred [24]. Microalgae are eukaryotic photosynthetic microorganisms with unique characteristics and versatile metabolism, making them a successful renewable resource for biofuels and bioproducts [25,26]. Ahmad *et al.* [27] discussed the potential of microalgae in the bioremediation of municipal and industrial wastewaters. Previous research has discovered several efficient microalgal strains, viz., *Dunaliella salina* [28], *Nannochloropsis* sp., and *Scenedesmus* sp., [29] in bioremediation of nutrients from dairy, agriculture

and swine wastewater, respectively. Ghazal *et al.* [30] investigated on textile wastewater as growth medium for five strains of microalgae, viz, *Chlorella vulgaris*, *Anabaena variabilis*, *Anabaena flos aquae*, *Nostoc linkia* and *Nostoc ellipsosporum*. The findings illustrated that BOD and COD value of the textile wastewater had significantly reduced when compared to control experiment. Furthermore, a study by Henkanatte-Gedera *et al.* [31] has observed that BOD removal rates were consistent within 5 days retention time through 700L wastewater treatment by microalgae *Galdieira sulphuraria*. Likewise, Tchinda *et al.* [32] had conducted a wastewater treatment strategy via enclosed bioreactor and after 2 days of experiment, it was discovered that BOD was eliminated at the rate of $16.4 \pm 3.3 \text{ mg L}^{-1} \text{ d}^{-1}$. Cheah *et al.* [4] and Hariz *et al.* [33] have applied *Chlorella* sp. and *Scenedesmus* sp. in the POME treatment for biomass and lipid production. Wastewaters can provide the nutrients and water for the growth of microalgae and biomass production, which is later converted to biofuels and other valuable metabolites [34–36]. Therefore, studies are going on to find a novel and efficient treatment technology that is also sustainable towards energy and the environment.

This current review aims to provide an insight on the prospects of the treatment of POME and LL using microalgae with the simultaneous production of biomass. As the world is shifting towards sustainability and circular economy, implementation of this strategy may lead to both. The utilization of POME and LL for the cultivation of microalgae as nutrients and production of biomass, while simultaneous removal of pollutants present in them is critically discussed. The cost of using the medium is reduced and the biomass can be further used to obtain biofuels, bioplastics and other myriad products. Thereby making the overall process as economically viable and environmentally sustainable. The role of cultivation systems (open and closed pond) is vital in obtaining the enhanced biomass productivity and efficient remediation of wastewaters. The review provides an insight into the open systems and photobioreactors (PBRs) employed in various studies. The cultivation of microalgae in wastewater also contributes to sustainable development goals (SDGs) 2, 6, 7, 12, 14 and 15. Especially 6 and 7 which are based on clean water and energy and are emphasized in this review. The pollutants assimilation from wastewater and CO_2 biosequestration are discussed for environmental protection. The search results for bibliometric analysis in Scopus show that there are 24 and 18 papers published for the bioremediation of LL and POME respectively from 2011 to 2021 (Fig. 3), which shows that the review augments the aspect of bioremediation of LL and POME. Since the disposal of solid waste is inevitable at the landfills and the treatment of LL is a serious issue for landfill operators due to its varying composition and recalcitrant nature [21]. Generally chemical and physical methods are used to treat LL which are costly and continuously require skilled manpower. Therefore, bioremediation using microalgae can become an alternative, cost effective and efficient treatment method. While POME is an issue of serious concern for palm oil mill operators due the presence of very high COD, somewhere between 70,000 to 100,000 mg/L [37]. The review also discusses about the CO_2 sequestration potential of microalgae with simultaneous production of lipid rich biomass, which can further be utilized to obtain biodiesel thus contributing to the circular bioeconomy. Therefore, the review will serve as a reference for the stakeholders to implement microalgal bioremediation from lab scale to pilot and full scale.

The conventional treatment scheme illustrated in Fig. 4 for the treatment of LL and palm oil mill effluent is quite efficient and practical, but it seems that the problem is shifted to the pollution of secondary nature. the problems of concern associated with the conventional treatment processes usually established at the sites of palm oil mills and landfills are (i) production of excessive sludge (in United States about 13.8 million tons of dry solids are gener-

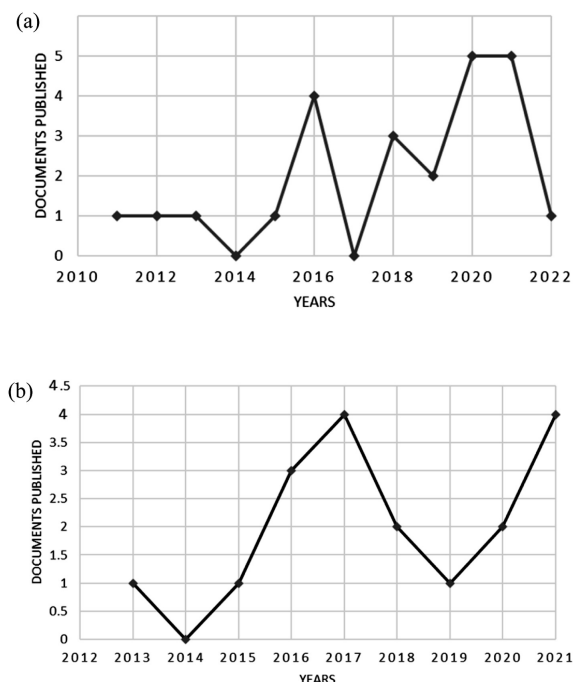


Fig. 3. Documents published on bioremediation of (a) LL and (b) POME using microalgae.

ated from 15,000 public treatment plants); (ii) excessive consumption of energy; (iii) direct or indirect source of the generation of greenhouse gases; and (iv) presence of toxic metals and recalcitrant compounds in the effluent and final sludge make it a more serious issue of disposal. Therefore to reduce the environmental and economic impact of wastewater treatment the researchers are exploiting all possible ways of the bioremediation of wastewaters using microalgae [38,39]. Some of the previous research and review papers which encompassed the bioremediation aspects for LL and POME are summarized in Table 2 [40–49].

2. POME treatment: POME as nutrients for microalgae growth

Microalgae are photosynthetic organisms that are constituted of eukaryotic cells and exist in unicellular and multicellular forms [50,51]. Cellular components of microalgae include plasma membrane, cell wall, nucleus, cytoplasm, and plastids. Plastids encapsulate chlorophylls that are accountable for nutrient transport via photosynthesis process. Comparing to higher plants, microalgae do not possess vascular system for food and energy manufacture since the entire cells are photoautotrophic that directly absorb nutrients [52]. Energy that is accumulated in chloroplast cells are assimilated by microalgae in the form of photons. Apart from that, microalgae ingest carbon dioxide that are expelled from bacterial respiration and exhaust gases through combustion altogether with growth nutrients from wastewater [53]. These uptake mechanisms ensure biomass synthesis and simultaneously generating oxygen [54].

Green microalgae perform photosynthesis like terrestrial plants. The photosynthetic mechanism in microalgae is the same as C3 plants, where ribulose biphosphate and CO_2 reacts to form 3-carbon acid [55]. While in heterotrophic and mixotrophic modes, microalgae can go for the assimilation of organic carbon. Other than carbon, phosphorus and nitrogen are the elements that are considered vital in the growth of microalgae. Numerous studies have been carried out globally to evaluate the microalgal potential in the bioremediation/treatment of wastewaters [56]. Microalgae can take up the nutrients and convert them into useful biomass.

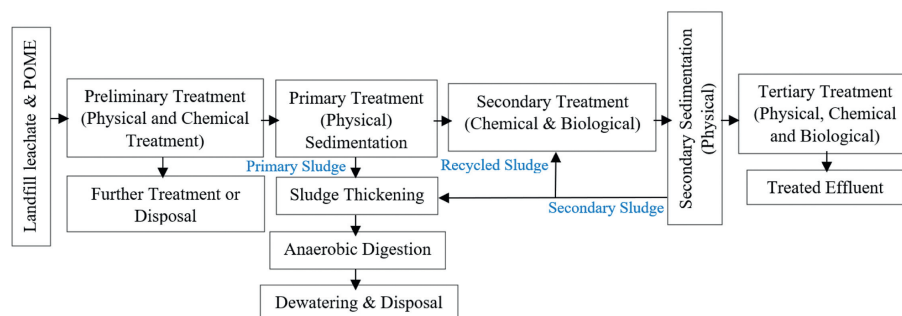


Fig. 4. Conventional treatment scheme adopted at the sites of palm oil mills and landfills.

As described by Emparan *et al.* [29], phosphate and nitrate utilisation by microalgae is vital for the growth of their cells and at the same time, can essentially aid in phosphorus and nitrogen depletion in wastewater. inorganic phosphorus is vitally responsible for growth and energy metabolism of microalgae. It exists naturally in proteins, lipids and nucleic acids. In microalgal metabolic process, monohydrogen phosphate ($[\text{HPO}_4]^{2-}$) and dihydrogen phosphate ($[\text{H}_2\text{PO}_4]^-$) are assimilated into adenosine diphosphate (ADP) via phosphorylation. This uptake process necessitates energy to yield adenosine triphosphate (ATP) which is the final product.

Electron transport system of mitochondria in microalgae which is the respiratory substrate carries out oxidation, generating energy and light that are needed for phosphorylation and photosynthesis processes, respectively [29]. In addition, photosynthesis incorporates both redox and photochemical reactions. To integrate ATP and NADH (reduced nicotinamide adenine dinucleotide phosphate) which are the energy storage molecules, light energy is used.

On top of that, organic nitrogen is the cornerstone in almost all molecular compounds like chlorophylls, ADP, ATP, proteins, enzymes, and peptides. Nitrogen gas (N_2), nitric acid (HNO_3), nitrite (NO_2^-), nitrate (NO_3^-), ammonia (NH_3), and ammonium (NH_4^+) are all inorganic nitrogen and can accumulate organic nitrogen in wastewater via sewage effluent. Microalgae can assimilate inorganic nitrogen to become organic nitrogen that takes place across the microalgal plasma membrane. In brief, the conversion mechanisms are the nitrite formation from nitrate reduction, and eventually to ammonium. Later, ammonium is transformed into amino acids. The foremost step of nitrate assimilation encompasses transfer of two electrons by nitrate reductase in the reduced form, namely, nicotinamide adenine dinucleotide (NADH), $\text{C}_{21}\text{H}_{27}\text{N}_7\text{O}_{14}\text{P}_2$. Thereafter, ferredoxin (Fd) works together with NADPH ($\text{C}_{21}\text{H}_{29}\text{N}_7\text{O}_{17}\text{P}_3$) (nitrite reductase) that is generated from photosynthesis transfer six electrons in order to reduce nitrate to ammonium. This reaction will reduce all inorganic nitrogen to ammonium which happens therein microalgal intracellular fluid. Lastly, glutamic acid (Glu), or in other word, the neuroactive amino acids found in microalgae alongside ATP integrate ammonium into amino acids, which in particular is glutamine [29].

The robust nature and versatile metabolism of microalgae assist them to survive in the typical environment of wastewater, and helps in its treatment [27]. Therefore, little or no freshwater is consumed during its cultivation. Moreover, the cost can be reduced as microalgae can assimilate nutrients from wastewater [57]. All the necessary nutrients (N, P, K, Mg, Fe, Zn, Ca) present in POME are required for microalgae growth. Microalgae advocate the aerobic bacterial oxidation of organic matter, producing photosynthetic oxygen, which catalyzes POME treatment, especially in terms of high BOD and COD. Microalgae also have the potential to detoxify, transform and volatilize the heavy metals present in POME [25]. The removal efficiency of *Characium* sp. and *Chlorella vulgaris* for nitrogen and phosphorus are 80%, 89.9%, and 86%, 78%, respec-

tively. Table 3 [58] shows the optimal conditions for microalgae growth in POME. It should also be noted that typical optimal conditions varied following microalgae species and types of cultivation systems applied.

Most microalgae species have the capability in nutrients removal. The nutrients have been reduced up to 94% by *N. oculata* as reported by Shah *et al.* [59]. Meanwhile other species removed more than half of its original concentrations. It has been reported that the concentration of nitrate required for the efficient growth of microalgae is ranging from 200 mg/mL to 400 mg/L. At the same time, minerals such as K, Mg, Zn, Ca, P, and Fe that are required for microalgal growth are also present in POME [4]. This makes POME a source of nutrients for the growth of microalgae. The highest biomass productivity of $0.52 \text{ g L}^{-1} \text{ d}^{-1}$ of *N. oculata* was as well observed along with highest nutrients removal. Table 4 [4,5,59–62] summarized the nutrient uptake capability and biomass productivity of various microalgae species.

The utilization of POME as a nutrient source for the cultivation of microalgae is indeed a well-accepted scheme in Malaysia. Millers prefer the cultivation of microalgae with POME as a tertiary treatment before discharging it to the environment because of its high efficiency and low cost. Fig. 5 shows the methodological design showing the feeding of POME to the microalgal pond. Most nutrients like orthophosphate and nitrate, which are not removed by anaerobic digestion, will undergo further treatment in microalgal ponds. Even after secondary treatment, total nitrogen content in POME is high compared to the discharge limit (200 mg/L) [63]. Meanwhile, nitrogen is a vital parameter required for the growth of microalgae. Therefore, the removal of nitrogen using microalgae is able to contribute to the overall treatment system. In this integrated system concept, biofuels production from microalgae cultivated in POME can be attained together with wastewater treatment and mitigation of air pollution.

2.1. Landfill leachate treatment: LL as nutrient for microalgae growth

Nitrogen (N) being an essential nutrient for the growth of microalgae, therefore using microalgae as a tertiary treatment of LL has been considered sustainable by researchers in the last couple of years [64]. Other than nitrogen (e.g., $\text{NO}_2\text{-N}$, $\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$), other pollutants present in LL (e.g., $\text{PO}_4\text{-P}$ and metals) are utilized by microalgae as the source of nutrients. By this approach, microalgae are grown in LL as a culture medium contributing towards its remediation and the cultivated biomass is processed to obtain biofertilizers, biofuels and other bioproducts.

Microalgae can further be utilized for CO_2 sequestration because it uptakes the gas from the biogas generated at the industrial plants as well as landfills [65,66]. The growth of microalgae in LL depends on various parameters such as light, pH, temperature, CO_2 & O_2 , inhibitors, and particularly the presence of nutrients like N and P. It was shown that mixtures or consortium of microalgae

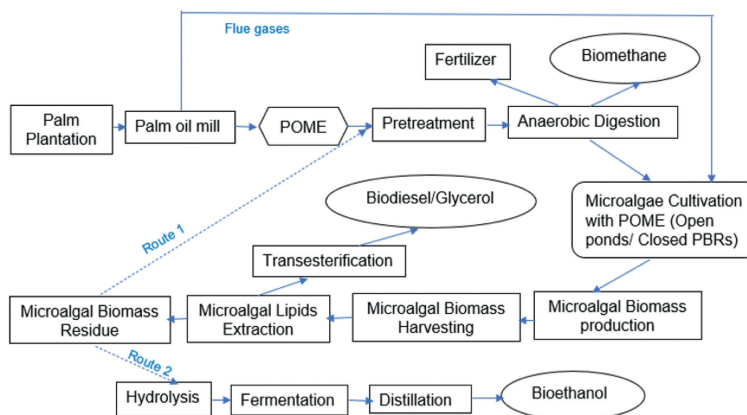


Fig. 5. Overview process of palm oil mill effluent treatment using microalgae.

species have contributed to nitrogen and phosphorus removal of up to 90% in most of the study, followed by COD removal. Nitrogen and phosphorus are undoubtedly the most preferred source of nutrients for microalgae growth. It could be seen that nutrients removal using microalgae cultivation, are considerably viable.

Phosphorus (P) is of vital important in cell metabolism. The consumption of P is going on at a faster rate posing the risk of depletion of nonrenewable phosphate rock (PR) [67]. Fertilizers containing $P-PO_4^{3-}$ are inevitable to produce 4F (e.g., fuel, food, fibre and feed). Therefore, the recycling and recovery of P are essential to sustain agricultural productivity. LL contain excess phosphorus and nitrogen, causing harmful impacts on the ecosystem, i.e., depletion of oxygen killing aquatic life, cyanotoxin production, eutrophication, and pH fluctuation [68]. Studies are therefore focusing on inorganic phosphate (Pi) removal for wastewaters in an efficient manner, simultaneously recycling and recovered. Phosphorus is regarded as an essential macronutrient required for microalgae growth as its deficiency may lead to lower cell densities. Although the necessary quantity of P in microalgae is up to 1%, studies reported that some microalgae species could accumulate even more P (~3.3%) [69]. P's cellular assimilation however varies with different species and cultivation conditions (nutrients, osmotic shock, light) [70].

This luxury uptake of P by microalgal species was investigated, and the assimilation was in the form of Poly-P. Poly-P is a biological polymer consisting of the remains of Pi and formed by phosphohydride bonds that have high energy and augment cell resistance during adverse environmental conditions [71]. Dyhrman [72] revealed that Poly-P has a significant role in/as a buffer to counter alkali conditions, DNA competence, a metal chelator, osmotic regulator, and energy storage compound. *Synechococcus*, *Chlamydomonas*, *Nostoc*, *Skeletonema*, *Thalassiosira*, *Synechocystis*, and *Calothrix*, etc. are effective in P removal [73]. In a study conducted by Khanzada [74], LL obtained after ultra-membrane treatment was fed as a nutrient for the growth of *Chlamydomonas reinhardtii* and *Chlorella vulgaris*, and it was found that 69.3% $N-NH_4^+$ removal was achieved when 100 mg/L of $P-PO_4^{3-}$ is supplemented to the medium. While P removal was observed to be 100% for all the concentrations of $P-PO_4^{3-}$. The stored granules of $P-PO_4^{3-}$ were detected by fluorescence microscope and subsequently this stored P can be obtained from the microalgal biomass was used as biofertilizers. The growth, biomass production, and nutrient assimilation capability of various microalgae species are shown in Table 5 [75–84]. The growth of microalgae in LL is practically viable after going through effective pre-treatment method or series of dilution.

2.2. Heavy metals, pathogens and pesticides removal

Microalgae have been proven to play an essential role in heavy metals uptake and can be divided into two; biosorption (extracellular binding) and bioaccumulation (intracellular binding). Biosorption is a swift uptake mechanism, and it surrounds the synergy between live microalgal cells and dead biomass which work together in performing active and passive biosorption, respectively. The surface of microalgal cells contain functional groups like sulfhydryl (-SH), amino (-NH₂), hydroxyl (-OH) and carboxyl (-COOH). According to Chan *et al.* [25] cationic metal ions are adsorbed physically unto cell surface of microalgal cells during passive biosorption. On the other hand, the metal ions are transported into the cytoplasm through cell membrane during active biosorption. Heavy metals like zinc (Zn), copper (Cu), titanium (Ti), manganese (Mn), nickel (Ni), mercury (Hg), cadmium (Cd), and lead (Pb) can be sequestered by microalgal intracellular polyphosphate bodies. These bodies are also capable of providing storage influx. After metals are stockpiled intracellularly, the metal ions are translocated with certain organelles and compelled to metallothioneins and phytochelutins, which are metal binding ligands. Reduction, surface complexation, physical adsorption, chelation, ion exchange and chemisorption are different types of extracellular metal binding mechanisms [85].

Ghazal *et al.* [30] had reported that most microalgae strains that were incubated in wastewater have outstanding capability of heavy metal assimilation. All strains (e.g., *Chlorella vulgaris*, *Anabaena variabilis*, *Anabaena flos aquae*, *Nostoc linkia* and *Nostoc ellipsosporum*) demonstrated significant copper ion removal efficiency, revealing a total of more than 80% heavy metal reduction. In particular, assimilation by *N. ellipsosporum* has depicted percentage of reduction exceeding 95% in up taking all heavy metals. Generally, arsenic removal is relatively low amongst all strains except for *C. vulgaris* and *N. ellipsosporum*. Conversely, bioaccumulation or intracellular binding involves heavy metal ions assimilation into microalgal cells. It is associated with metabolism and comparatively torpid. Heavy metals are assimilated on microalgal surface and work together with enzymes on plasma membrane via sedimentation, complexation and crystallization, and eventually transported into the cells [86]. Aquatic environments like wastewater that are contaminated with heavy metals can be treated via microalgal cell bioaccumulation.

Other than that, microalgal role in treating wastewater also include removing pathogens. Dar *et al.* [87] explained that it is carried out through various mechanisms, i.e., pH elevation and level of dissolved oxygen, nutrients rivalry, algal toxins and pathogens adhesion and sedimentation. Nutrients and carbon sources are the major powerhouse for bacterial cells. Upon incubation, microalgae

Table 2
Summarizes the key objectives covered by various studies and the vast spectrum of this paper.

Key objectives incorporated										Studies
Landfill leachate	POME	Nutrients recovery (C/N/P/K)	Pollutants removal/HMs removal	Biomass productivity	Microalgae-bacteria interaction	PBRs employed	Lipid/other metabolites accumulation/FAME composition	Production of biofuels/bioproductions	Circular bioeconomy	
✓	x	✓	x	✓	x	✓	x	x	x	[40]
✓	x	x	x	✓	x	✓	✓	✓	x	[41]
✓	x	✓	✓	✓	x	✓	✓	✓	x	[42]
✓	x	✓	✓	✓	x	x	✓	✓	x	[43]
✓	x	✓	✓	✓	✓	x	✓	✓	x	[44]
✓	x	✓	✓	✓	✓	x	✓	✓	x	[45]
x	✓	✓	✓	✓	x	x	✓	✓	x	[46]
x	✓	✓	✓	✓	x	x	✓	✓	x	[47]
x	✓	✓	✓	✓	x	x	✓	✓	x	[48]
x	✓	✓	✓	✓	x	✓	✓	✓	x	[49]
✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	This paper

Table 3
Optimal conditions for microalgae growth in POME [58].

Growth parameters	Optimal range/value
pH	8.2–8.7
Salinity (g/L)	20–24
Nutrients	N:P (16:1)
Temperature (°C)	18–24
Light Intensity (Lux)	2500–5000
Photoperiod (Light: Dark)	16:8 (minimum)–24:0 (maximum)
CO ₂ rate	1% of volume in air

Table 4
Nutrient uptake and biomass production of microalgae cultivated in POME.

Microalgae species	Nutrient reduction (%)	Biomass productivity (g L ⁻¹ d ⁻¹)	Duration (day)	Ref.
<i>Chlorella sorokiniana</i>	92	0.19	7–14	[4]
<i>Chlorella sorokiniana</i>	62	0.15	7–14	[5]
<i>N. oculata</i>	94	0.52	7	[59]
<i>Chlamydomonas</i> sp.	68	0.08	7	[60]
<i>C. pyrenoidosa</i>	71	0.13	10	[61]
<i>T. suecica</i>	95	0.21	7	[62]

would need to ingest carbon and nutrients as well, resulting in nutrients rivalry between bacteria and microalgae. This competition poses threat to bacterial growth, leading to bacterial cells cessation. In the meantime, microalgal cultivation typically has high value of pH due to carbon dioxide uptake during photosynthesis. Concurrently, nitrogen ingestion by microalgae elevates pH value of the growth medium since there is one OH ion produced (ammonia) in every reduction of nitrate ion. All in all, and together with microbial oxygenation, pathogens are easily eliminated. Microbial oxygenation occurs during bacterial respiration in treatment system that aids in algal growth, and it has been discovered as the reason of faecal bacteria eradication due to oxygen toxic formations.

During the phenomenon by microalgae of dissolved oxygen and pH increment, faecal bacteria adhesion to microalgae is crucial because it guarantees close proximity of bacterial cells. In order for adhesion to take place, solid matter must first be attached with pathogens, and it will descend as sediment and precipitate on microalgal cells. Thereupon, bacterial polysaccharides will produce positive charge polymers (amino groups) to neutralize negative charge of microalgal surface. Subsequently, a bridge will be generated between these particles and help bacterial cells to attach to microalgae [87]. According to an experimental result by Mezari *et al.* [88], *Scenedesmus* sp. had eminently removed pathogen *Salmonella enterica* under mixotrophic condition within 48 h of retention time. Additionally, coliform bacteria altogether with total suspended and dissolved solids, phosphorus, nitrogen, COD as well as BOD were reported to be eliminated by *Rhizoclonium implexum* [87]. Tchinda *et al.* [32] mentioned the capability of *Galdiera sulhuraria* in mitigating coliform bacteria *Escherichia coli* and *Enterococcus faecalis* within 3 days of incubation to significantly low levels.

Furthermore, pesticides are also one of the organic pollutants that microalgae thrive upon incubation to be assimilated as their energy source via biodegradation and biosorption. Disintegration of bonds in pesticides molecules by enzymes secreted by microalgae induce biodegradation. *Chlorella vulgaris* was subjected to four typical fungicides, viz. metalaxyl, propamocarb, cyprodinil and mandipropamid in a study by Ardal [89]. The experiment involved short-term biosorption and long-term biodegradation for 60 min and 4 days, respectively. The result in both short- and long-term investigations revealed that *C. vulgaris* effectively eradicate the most of cyprodinil and followed by mandipropamid.

Table 5
Studies on the nutrient uptake and biomass production of microalgae treatment of LL.

Type of LL	Cultivation system	Species of microalgae	NH ₄ ⁺ -N removal	P removal	COD removal	Biomass (g/L)	Biomass production (mg L ⁻¹ d ⁻¹)	Ref.
Filtration, dilution, and autoclaving	Batch; 250 mL flask	<i>Scenedesmus</i> sp.	(16.8 mg/L) 84%	(0.22 mg/L) 80.5%	-	0.75	37.5	[75]
Pre-treated mechanical aeration) Daily 1% to 4% medium is replaced by LL	40 L open raceway pond; Semi continuous	<i>Scenedesmus quadricauda</i> <i>Euglena gracilis</i> , <i>C. vulgaris</i> <i>Ankistrodesmus convolutus</i>	99.9%	86%	-	5.5	-	[76]
Raw LL (10%) Filtered and diluted load (30%–60%) Pre-treated; KH ₂ PO ₄ supplemented	Batch; 250 mL flask 150 mL flask 1 L flasks	<i>Chlorococcum oviforme</i> <i>Scenedesmus</i> sp. <i>Chlamydomonas</i> sp. <i>C. vulgaris</i>	40%–55% 83%	75% 95%	-	- 1.21	-	[77] [78]
Raw LL (Filtered) >12 years	Batch; 500 mL flask	<i>Chlorella pyrenoidosa</i>	22%–100%	38%–100%	-	0.81–1.71	20–110	[79]
Raw LL >20 years	Pilot scale 20 m ³ , stabilization pond system, 200 L/d	Consortia of Bacteria & Microalgae	75%	70%	75%	-	-	[80]
Filtered LL	Batch scale, 500 mL	<i>Chlorella pyrenoidosa</i> + Bacteria	75%–99%	-	35%–82%	-	-	[81]
Autoclaved LL	1000 mL, batch scale.	<i>Chlorella</i> sp.	90%	95%	-	-	-	[82]
Raw LL	Microbial fuel cells	Mixed algae from domestic wastewater	60%–90%	-	4%–60%	-	-	[83]
			80.6%–98.7%	0%–80.28%	52%–97%	-	-	[84]

3. Bioreactors or cultivation systems for microalgae growth

The essential factors responsible for microalgal cultivation are sufficient nutrients, sunlight, and CO₂ [90]. Thus, an optimum and efficient design of the cultivation system is required to maximize biomass productivity. The cultivation systems can be classified into open and closed photobioreactors (PBRs), both having their respective advantages and disadvantages [91]. Open systems include simple ponds, centrally pivoted circular ponds, tanks or lagoons, cascade systems, and raceway ponds. While the close PBRs include horizontal, flat panel, vertical or inclined, tubular, helical, membrane, floating and hybrid units. Open ponds are economical but posing drawbacks such as loss of water due to evaporation and vulnerability to contamination by other microorganisms. Since it is susceptible to contamination, this problem may aggravate when POME is utilized as a source of nutrients. As POME contains high values of COD and BOD, this may lead to the growth of other unwanted microorganisms and ultimately inhibit microalgae biomass yield [92]. In the PBRs, the use of costlier materials for their buildup and additional equipment in their periphery for CO₂, air, and chemicals increases their capital and operational expenditures, compared to open systems. Nevertheless, closed PBRs help protect culture from contaminants facilitating improvised growth and increased productivity. In closed PBRs, growth factors like temperature, pH, CO₂ concentration, and nutrients can be controlled and regulated. Furthermore, the risk of contamination can also be overcome in closed PBRs. However, the bottleneck of this system is high operational expenditure in commercialization, but it can be compensated by using POME from secondary treatment as a nutrient source and culture medium [4]. Palm oil mills are usually considered to be self-reliant in terms of energy. Oil palm biomass such as shell and fibre, are utilized as the fuel for the boiler to generate electricity and steam for the process of sterilization. Sometimes, if this energy is surplus, it can be supplied to nearby community usage [93]. Hence an option to utilize this extra energy is for running the PBR system (i.e., artificial light, pump and temperature control devices). If this strategy works efficiently, the operational expenditure of microalgae cultivation can be reduced considerably. However, this strategy needs to be reinforced by the life cycle assessment [94]. Till date, due to the economic aspect consideration, most of the commercial scale cultivation of microalgae is conducted via open systems. Microalgae cultivation in open systems is employed to treat municipal, industrial, and agricultural treatment facilities. Most of the used open systems are stabilization ponds or lagoons and high-rate algal ponds (HRAP). HRAP enables the symbiotic action of microalgae and bacteria. In this system, the oxygen generated by the photosynthetic growth of microalgae is consumed by aerobic bacteria to degrade organic matter present in LL to CO₂, which is sequentially utilised back by microalgae as a carbon source [95]. Cheah *et al.* [6] has reported on co-cultivation of *Chlorella sorokiniana* and *Pseudomonas* sp. in POME, at ratio of 1:1. Biomass concentration and productivity of 2.04 g/L and 185.71 mg L⁻¹ d⁻¹, were attained, respectively. Fig. 6 shows the schematic diagram of microalgae cultivation systems.

There was study carried by Casazza and Rovatti [96] revealed the reduction of nitrite, nitrate and ammonia from LL. The experiment was conducted in a vertical PBR having 1.5 L capacity with a bubbling effect and artificial lighting with the help of fluorescent lamps. Biomass concentration obtained was 2 g/L after 28 days of cultivation, and it resulted in 100% removal of nitrate and ammonia together with partially removing the nitrite. Another study by Chang *et al.* [97] employed a membrane PBR to mitigate the effect of inhibitory compounds. The membrane only allowed inorganic ions (e.g., phosphate and ammonium) to get diffused from the LL compartment to the microalgae cultivation chamber, thus blocking the suspended solids to pass through, which can inhibit the

growth of microalgae. The study made by Cheah *et al.* [98] shows that the cultivation of *Chlorella sorokiniana* CY-1 in POME employing novel designed PBR (e.g., flat panel and acrylic) has resulted in increased biomass production, good lipid content and productivity, and successful POME remediation. The pollutants removal efficiencies achieved were 93.7% of chemical oxygen demand, 98.6% of total nitrogen and 96.0% of total phosphorus. Thus, signifying the importance of photobioreactor in the cultivation and bioremediation. This application may have aided in the development of more efficient biofuels and wastewater bioremediation, allowing for environmental sustainability.

The proteins derived from the microalgal biomass can be utilized to produce pigment, biofertilizers and antioxidants [18]. Carbohydrates and lipids could be used for bioethanol and biodiesel production [99]. Furthermore, after the bioenergy valorization, the microalgal biomass residue produced from LL can effectively apply to the soil as a biofertilizer, thus becoming a sustainable alternative to chemical fertilizers [100]. Table 6 [42,101–103] provides information on the biochemical composition of the biomass cultivated using LL treatment.

4. Role of microalgae in CO₂ sequestration and circular bioeconomy

About 14–161 kg of CO₂ emissions occurs for every single tons of crude palm oil production [104]. It was reported that the annual emissions of CO₂ during the production of palm oil was about 1200–4900 million kg CO₂ [4]. This has created an urgency in controlling and utilizing the CO₂ emissions from palm oil mill to assure its sustainability towards the environment. Microalgae has the ability for CO₂ sequestration from the atmosphere, soluble carbonate, or flue gases while taking up solar energy [66,105]. The most preferred method for microalgae to act as a carbon sink is by capturing CO₂ from the atmosphere, but this method is not so effective due to the low CO₂ concentration present in air. Additionally, another problem is the utilization of CO₂ due to the lower mass transfer rate of CO₂ into the water, as this could increase the cost of air pumping. Excessive amount of carbon dioxide that came from microbial respiration in wastewater system can trigger pH imbalance. This condition is beneficial for microalgae as they have amazing resistance against exorbitant atmosphere of carbon replete environment and are capable of assimilating carbon from atmospheric carbon dioxide and bacterial oxygenation [106]. Some of them are also efficient in pH neutralisation of wastewater. Generally, fixation of carbon generates final carbohydrate products as [CH₂O]_n. Carbon fixation activity can be categorised into two reactions that are light independent (dark) and light dependant reactions. During dark or light independent reaction, NADPH and ATP that are released from photosynthesis act as electron donors. Meanwhile, during light dependant reaction like oxygenic photosynthesis, water acts as the electron donor and oxygen is discharged after hydrolysis process. Then, the co-produced carbon skeletons during light and dark reaction modes are utilised in a wide range of consequential processes, configuring into other organic compounds. For instance, cellulose, a type of carbohydrate can be employed as a kickstart for amino acids and lipids biosynthesis in which justifies the structure of carbon dioxide fixation process. Oxygen is also discharged from this reaction whereupon it is absorbed by bacteria as to decrease high number of organic matters in wastewater effluent by microbial metabolism, thus promoting wastewater bioremediation [107].

Nevertheless, some microalgal species have versatile metabolism to adapt to the high concentration of CO₂ present in flue gases. *Botryococcus braunii*, *Chlorella* sp., and *Scenedesmus* sp. are reported as potential microalgae species for CO₂ mitigation from flue gases while producing appreciable lipid content for

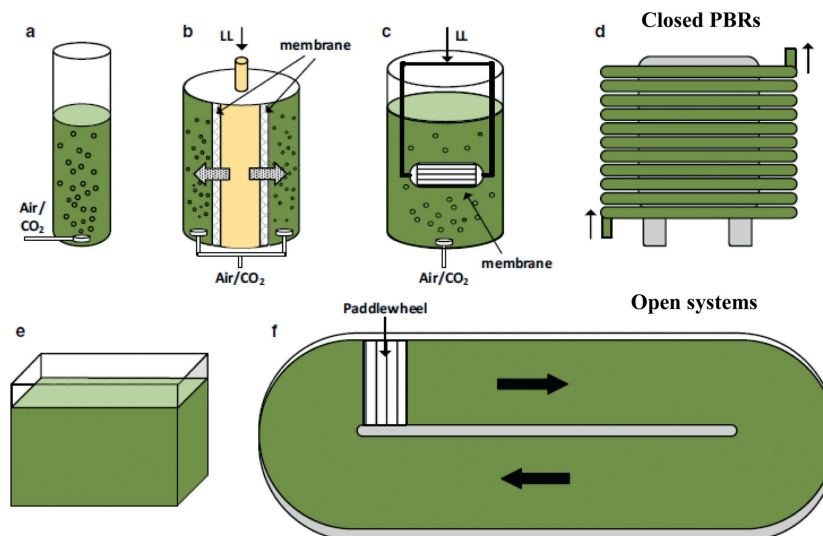


Fig. 6. Schematic diagram of microalgae cultivation systems: (a-d) Closed PBRs and (e, f) open systems. Copied with permission [20]. Copyright 2020, Springer Nature B.V. 2020.

Table 6

Biomass composition of microalgae cultivated using LL.

Wastewater Effluent	System for experiment	Carbohydrates	Proteins	Lipids	Bioproducts	Ref.
20% LL solution	Bubble column PBR	19.7	37.1	16.6	Multiple applications	[42]
50% LL solution (v/v)	Membrane PBR(320 mm height), 25–28 °C, 9000 lx	–	–	38	–	[101]
Municipal wastewater solution + 7% LL	Bottle with working volume of 4 L (53 $\mu\text{mol m}^{-2} \text{s}^{-1}$ with cycles of 12:12)	25	–	15	Biofuels	[102]
10% LL solution (v/v)	PBR in sequencing batch mode (76 $\mu\text{mol m}^{-2} \text{s}^{-1}$)	21.5	9.7	13.8	–	[103]

subsequent ensuing biodiesel production [108]. Since *Botryococcus braunii*, and *Scenedesmus* sp. are freshwater microalgae species, they can be easily found in Malaysia and other tropical countries. Therefore, utilizing flue gases containing CO_2 from the palm oil milling process and to cultivate microalgae using POME as the source of nutrients, are considerably feasible. Microalgae also support the bacterial oxidation of organic matter and during this course of action, it produces oxygen by photosynthesis, which contributes to the treatment of POME [109]. This characteristics of microalgae have contributed in lowering down COD and BOD concentrations, which are otherwise very high in POME [110]. Furthermore, microalgae have immense potential for nutrient uptake as they utilize phosphorus and nitrogen for nutrition in their growth. Microalgae can also detoxify and volatilize the heavy metals present in POME by its unique metabolism [4]. Therefore, using microalgae for biosorption in the removal of heavy metals from wastewaters is a feasible process [25]. Since microalgae contain proteins, lipids, and polysaccharides at the surface of cell walls, they have some functional groups like hydroxyl, sulphate, amino, and carboxyl that can work as binding sites for the heavy metals [111,112].

Recently, researchers have been more interested in circular bioeconomy and are developing algal-based biorefineries as cutting-edge green technologies. The term ‘bioeconomy’ refers to the sustainable provision of necessary utilities and advantages to all economic cross sections through the scientific use and production of natural biological resources as well as innovation-orientated biological methods and principles. A “circular bioeconomy” can be characterised as a sustainability concept that aims to reduce or limit the use of primary resources by enhancing resource recycling and recovery [113]. Resource depletion and environmental degra-

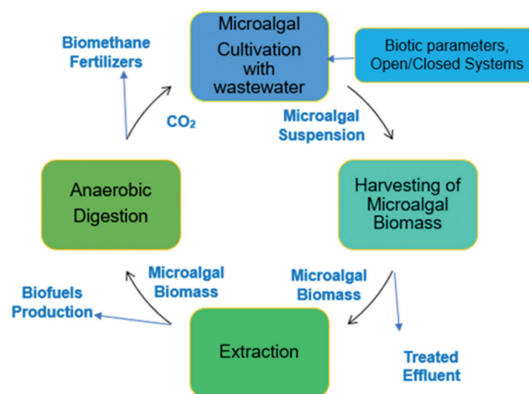


Fig. 7. Cultivation of microalgae leading to circular bioeconomy.

dation can be improved in a financially viable way with the help of the circular bioeconomy. Utilizing microalgal biomass as a necessary component to manufacture bioenergy, biochemicals, and other bioproducts is part of the microalgal bioeconomy concept. The production of biomass, biofuels, and other bioproducts can be combined with microalgal wastewater treatment to achieve effective outcomes [114]. Fig. 7 illustrates the treatment of wastewater using microalgae also contributes to circular bioeconomy and environmental sustainability.

Sustainable development is the foundation of a country's environmental, economic, sociological, and public health ideals. The SDG framework was created for and endorsed by UN member countries for the long-term transformation of people's and planet's well-being. However, the failure of the SDGs to be achieved sug-

Table 7
Contribution of microalgae in achieving various SDGs.

SDG	Contribution of microalgae	Ref.
SDG-2 Zero hunger	Production of protein, PFAs for food, feed, and health supplements	[115]
SDG-6 Clean water and sanitation	Treatment of wastewater by the nutrient uptake and conversion to rich biomass; Bioremediation of emerging contaminants via biodegradation, bio uptake or bio-adsorption; Disinfection of pathogens in HRAPs by high pH and DO due to photosynthetic reaction	[116]
SDG-7 Affordable and clean energy	Third generation biofuel like biogas, biodiesel, bioethanol, and butanol can be produced	[117]
SDG-12 Responsible consumption and production	Bio plastic can be produced by: Biomass; Blending of synthetic plastic with microalgal plastic and obtain hybrid plastic; Production from the cellular fraction of micro algae	[118]
SDG-14 Life below water	Nutrient assimilation into filamentous algae biomass grown in artificial flow ways for the bioremediation of diffused pollution.	[119]
SDG-15 Life on land	Bio stimulants generated from microalgae to enhance crop plant growth and yield, stress tolerance of plants, condition and stability of soils and reduced fertilizer applications	[120]

gests that current technologies are inadequate to balance environmental, economic, and societal objectives, and that technological advances are needed to achieve the SDGs. Emerging uses of microalgal biotechnology show that these organisms have the potential to help meet a number of UN SDGs. The contribution of microalgae in achieving different SDGs is shown in Table 7 [115–120].

Direct use of microalgae biomass, blending with other materials, intermediate biorefinery processing, and genetic engineering to establish suitable polymer-producing microalgae strains are all options for making microalgae-based bioplastics. Algal biomass contains protein and carbohydrate-based polymers, which can be used as a component of bioplastics. Currently, algae biomass constituents such as starch, cellulose, PHA, PLA, PHB, PVC, PE, and protein-based polymers are being employed to make biodegradable plastics [121]. There have been several examples of bioplastics that have been made by designers or researchers. For example, Dutch designers Eric Klarenbeek and Maartje Dros developed a bioplastic product manufactured from algae that might replace conventional plastics. They also built AlgaeLab to culture algae to produce starch as a bioplastic raw material [122].

Austeja Platukyte also produced biodegradable materials made of algal agar and coated calcium carbonate that might be used to replace petroleum-based polymers. The final products are lightweight but waterproof, sturdy, and long-lasting. Furthermore, bioplastics can be decomposed or used as fertiliser to aid in soil moisture retention. Ari Jonsson made an alternative bottle to the usual plastic bottle by mixing red algal powder with water. The liquids in the container are safe to drink, and customers can also munch on the bottle itself. The encapsulation of nonbiodegradable polymers, such as polyolefin, in thermoplastic algal blends can absorb and permanently keep carbon dioxide in the form of biomass during the manufacture of algae-based plastic. As a result, no carbon dioxide will be released into the atmosphere, reducing the greenhouse impact. To summarise, algal-based bioplastics are a viable and nontoxic alternative that can reduce the use of fossil fuels, improve plastic quality, and lessen negative environmental effects caused by the excessive use of petroleum-based plastics, as well as solve the problem of ocean plastic pollution [123].

4.1. Biomass productivity and lipid accumulation of microalgae using POME medium

Microalgae is recommended as a potential feedstock to produce biofuels because of their fast growth rate as compared to other terrestrial plants, high content of lipids and lesser area requirement. Therefore, microalgae cultivated with POME can be utilized to produce biodiesel. As it is quite important in Malaysia, which is the world's second leading producer of palm oil, having about 457 palm oil mills generating massive amount of palm oil mill effluent (POME) daily [124]. The quality of biodiesel obtained from

microalgal biomass depends upon the lipid content, biomass productivity, and fatty acid content. *Chlorella* sp. is well-known species which is being used for POME treatment and biodiesel production as its biomass can accumulate a considerable amount of lipids under stress [125]. *Chlorella* sp. was cultivated with POME using different types of bioreactors, so it was found that the biomass obtained was rich in carbohydrates, lipids, and proteins. Subsequently, the biomass obtained can be converted into biodiesel and other bioproducts [126]. The productivity of biomass and lipids by cultivating *Chlorella* sp. with POME was exhibiting comparative yield than using standard growth medium. Furthermore, life cycle assessment of the microalgae cultivation with POME to produce biofuels has also shown its feasibility [127]. The solution for cost-effective microalgae production has been identified as microalgae growing in wastewaters. The study by looked into the viability of employing POME for *Chlorella* sp. cultivation to produce biomass and lipids. To promote biomass and lipid productivities, the best POME concentration and pretreatment approach were used. When grown in acid-heat pretreated 30% (v/v) POME, *Chlorella sorokiniana* CY-1 had a maximum lipid content of 11.21% and a biomass concentration of 2.12 g/L. This results in a higher yield than the values provided on POME. Pretreatment has been shown to increase biomass production by converting lignin in POME to reducing sugars, which can then be used as a supplement. The removal efficiencies for TN, TP and COD were 62.07%, 30.77% and 47.09%, respectively. This increases the practicality of microalgae growing for biofuel production while also contributing to environmental sustainability. The production of biofuels from microalgae is based on its cellular lipid content. Therefore, bio-engineered modification techniques within the cells can as well effectively improving the lipid productivity. The biomass and lipid productivity of various microalgae species cultivated with POME are summarized in Table 8 [4,128–131]. Various studies have concluded that POME is an accepted medium for the cultivation of microalgae in biodiesel production. It should be noted that, to best of authors knowledge, the study related in biomass and lipid productivity using LL is still scarce in the literature research, therefore this section documented microalgae performance in POME.

4.2. Biofuels production from microalgae cultivated in POME

After harvesting microalgae from open systems or closed PBRs, it is subsequently subjected to dehydration [90]. After the completion of dehydration process, the dried microalgal biomass goes through the process of cell destruction to extract lipids from microalgal cells. Finally, the lipids after extraction are subjected to the transesterification reaction where biodiesel is obtained as the main product and glycerol as the by product. Homogenous base catalysts like KOH and NaOH are used during transesterification to react at a

Table 8
Biomass and lipid productivity of microalgae species grown in POME.

Microalgae species	Cultivation medium	Max. biomass concentration (g/L)/biomass productivity (g L ⁻¹ d ⁻¹)	Lipid content (%)/lipid productivity (g L ⁻¹ d ⁻¹)	Ref.
<i>Chlorella sorokiniana</i> CY-1	30% (v/v) POME	1.86/0.13	9.97/0.08	[4]
<i>Chlorella sorokiniana</i> CY-1	Pre-treated 30% (v/v) POME	2.12/0.15	11.21/0.07	[4]
<i>Chlorella</i> sp.	60% (v/v) POME + 80% synthetic nutrients	0.59/0.269	7.6/0.1	[128]
<i>Chlorella vulgaris</i>	40% (v/v) POME + D-glucose	1.43/-	9.7/0.2	[129]
<i>Chlorella pyrenoidosa</i>	250 mg/L POME in BBM + 1 mL chloramphenicol	-/0.003	21.51/-	[130]
<i>Tetraselmis</i> sp.	250 mg/L POME in BBM + 1 mL chloramphenicol	-/0.04	25.69/-	[130]
<i>Botryococcus sudeticus</i>	POME	1.03/-	26.6/-	[131]
<i>Chlorella vulgaris</i>	POME	1.47/-	15.1/-	[131]

Table 9
Carbohydrates and proteins composition of microalgae species (dry matter basis, %).

Microalgae species	Carbohydrate (%)	Protein (%)
<i>Chlamydomonas reinhardtii</i>	17	48
<i>Chlorella vulgaris</i>	12–17	51–58
<i>Chlorella pyrenoidosa</i>	26	57
<i>Euglena gracilis</i>	14–18	39–61
<i>Dunaliella salina</i>	32	57
<i>Spirulina platensis</i>	8–14	46–63
<i>Scenedesmus obliquus</i>	10–17	50–56

mild temperature (50–80 °C) [132]. These catalysts are extensively used in biodiesel plants at commercial scale because of their low cost and easy availability [133,134]. To make biodiesel production from microalgae practically feasible and economically viable there should be optimized design of photobioreactor system, bulk scale cultivation of microalgae and enhanced lipid productivity. Microalgae also have the potential to produce bioethanol. Besides the high lipid composition utilized to produce biodiesel, microalgae also contain protein and carbohydrates that can be utilized as carbon sources for fermentation (Table 9). Therefore, microalgal lipids can be extracted for biodiesel production before being subjected to hydrolysis and fermentation processes to obtain bioethanol. Furthermore, after fermentation, the residual microalgal biomass can be used in anaerobic digestion to produce biomethane [135,136].

5. An overview of the treatment of various wastewaters using microalgae

Significantly nowadays, water bodies are adversely affected by discharges by commercial industries alongside water stream. Water pollutions give rise to various issues that are associated with shortage of clean and safe water for daily consumption and other critical domestic and industrial operations [137]. Pollutants might vary according to industry types, but nearly all wastewater that are formed consist of numerous contaminants such as heavy metals, volatile organic compound matters, minerals, pesticides, oil as well as grease. On top of that, certain accumulated pollutants like phosphorus and nitrogen altogether with eutrophic wastewater (e.g., industrial or sewer waste) could substantially impact both saltwater and freshwater ecological community. In ensuing assured safe human consumption and environmental wellbeing, the contaminated water must be treated in prior.

Interaction between algae and bacteria allows the released dissolved oxygen by microalgae to be consumed by bacteria, in order to degrade organic materials to water and carbon dioxide. This course of action explains that microalgae contribute essential oxidising agent, i.e., molecular oxygen for bacterial oxidation, which consequently decrease COD and BOD in wastewater. Ghazal *et al.* [30] investigated on textile wastewater as growth medium for five strains of microalgae, viz, *Chlorella vulgaris*, *Anabaena variabilis*, *Anabaena flos aquae*, *Nostoc linkia* and *Nostoc ellipsosporum*. The findings illustrated that BOD and COD value of the textile wastewater had significantly reduce when compared to control experiment. It was observed that nearly all microalgae exhibited efficient removal capacity which is more than 80%, except for *A. flos aquae*.

Chai *et al.* [138] described that it is substantial for the working temperature to be at maximum of 30 °C. This is due to continuous increment in percentage of BOD and COD removal rates, and it maximises at 30 °C. Experiment conducted beyond 30 °C would lead to microalgal cell cessation and reduced efficacy of oxygen demand elimination.

Next, dye removal has been identified as one of microalgal abilities in wastewater and bioremediation. Chu and Phang [139] explained that the affinity of binding and high surface area of microalgal cells enable them to remove vinyl sulfone dye and colour in textile wastewater. The types of mechanisms utilised by microalgae in discarding dyes are through complexation, electrostatic attraction, bioconversion and biosorption. Dye ions attach and amass to the surface of algal biopolymers and eventually dispersed into solid biopolymer. Biosorption of dye particles is facilitated by extracellular polymers onto the surface. Extracellular polymers are made up of surface functional groups which supported sorption of dye molecules aboard the polymer surface [140]. *Spirgyra* biomass is proven to be proficient biosorbent in eliminating reactive dye. Besides that, biomass of *Caulerpa scalpelliformis* and *Caulerpa lentillifera* are effective removers of basic dye particles via bisorption. During bioconversion, microalgae deteriorate dyes into simpler compounds. For instance, *C. vulgaris* is capable of degrading mono-azo dye into aniline as much as 63%–69% reduction [138]. According to Touliabah *et al.* [141], at least 30 types of azo dyes are biodegraded into simpler aromatic amines by *C. vulgaris* and *Chlorella pyrenoidosa*. Apart from that, Ghazal *et al.* [30] discovered the capability of several microalgae strains in eliminating red colouring of industrial textile effluent. The mentioned microalgae strains are *Chlorella vulgaris*, *Anabaena variabilis*, *Anabaena flos aquae*, *Nostoc linkia* and *Nostoc ellipsosporum*. The findings demonstrated diverse biodegradation percentage that is dominated by *N. ellipsosporum* with total dye removal activity and followed by *C. vulgaris* with 96.16% reduction activity. The next removal percent-

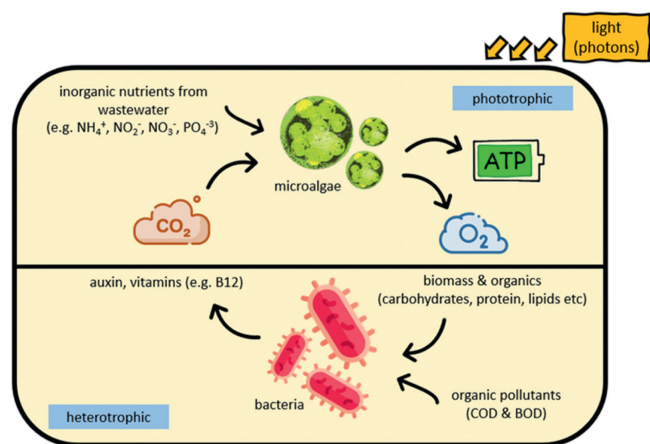


Fig. 8. Uptake mechanism of microalgae.

ages are resulted at 88.71%, 79.03% and 50.81% by microalgae *A. variabilis*, *N. linkia* and *A. flos aquae*, respectively. This concluded that the convoluted composition of textile effluent that are mixed with various chemicals does not influence dye removal activity of microalgae.

In terms of safety, affiliated pollution could be prevented because organic compound formation from water and carbon dioxide does not postulate additional energy. Dissipated oxygen from microalgae is sufficient enough in achieving the required bacterial aerobic environment to assimilate organic matter remnants in treated wastewater. Moreover, dark and light cultivation systems are necessary for efficient photosynthetic activities of microalgae whereby the former involves essential molecules biochemical synthesis for microalgal growth. Meanwhile, the latter is deployed for photochemical period in order to generate adenosine triphosphate (ATP) and nicotinamide adenine dinucleotide phosphate-oxidase (NADPH) [138]. Fig. 8 briefly illustrates integrated model of uptake mechanism by microalgae that is associated with bacterial oxidation in wastewater.

Bioremediation of wastewater by microalgae involves multifaceted actions ranging from nutrients elimination (phosphorus and nitrogen), reduction of BOD and COD, carbon dioxide fixation as well as biomass production. Several potentially toxic substances removal is also implicated such as heavy metals, dyes, pesticides, and pathogens. Currently, profound research investigations regarding wastewater treatment and recycling have been conducted [142]. Effective microalgae cultivation and bioremediation in wastewater is fundamentally reliant on adequate nutrients in wastewater (as growth medium) to guarantee functional cellular bio-synthesis and value-added biomass. Removal of essential substance that are dissolved in wastewater such as trace minerals, vitamins, micronutrients, macronutrients, phosphorus, nitrogen, biochemical oxygen demand (BOD), chemical oxygen demand (COD), toxic compounds (organic and inorganic) and other impurities is extremely advantageous towards optimum microalgal growth via their uptake mechanism. Additionally, this strategy is economically beneficial and viable notably with the existing environmental issues that are associated with hazardous chemicals in wastewater. Previous research has discovered several efficient microalgal strains, viz., *Dunaliella salina* [28], *Chlorella* sp. [33], *Nannochloropsis* sp., and *Scenedesmus* sp. [29], in bioremediation of nutrients from various sources of wastewater. Microalgae and bacteria interact in various ways, from symbiotic (i.e., mutualism) to competition (i.e., antagonism) [143]. The symbiotic interactions between microalgae-bacteria include nutrient exchange, cell-to-cell communication, and chemical compound stimulation. Mi-

croalgae may also detect quorum-sensing signal molecules, vitamins, and siderophores produced by bacteria, resulting in symbiotic relationships with improved bioactivity, elimination, and tolerance [144]. Creating a symbiotic relationship between microalgae and bacteria enhances wastewater treatment efficiency. As a result, a microalgae-bacteria consortium is a viable option for wastewater treatment and bioenergy generation. On the other hand, the antagonism effect is often negligible compared to the overall beneficial relationship. The antagonistic interactions occur when the decay of dead microalgae competes for oxygen with bacteria. Furthermore, microalgae and bacteria can produce a wide range of inhibitory compounds that can harm the partners growth [145].

Three local microalgae were used to remediate wastewater from a palm oil mill (POME) (e.g., *Chlamydomonas* sp. UKM6, *Coelastrella* sp. UKM4, and *Scenedesmus* sp. UKM9). Firmicutes, Bacteroidetes, Actinobacteria, Planctomycetes, and Proteobacteria were present in the raw POME. Both sterile and raw POME had their nitrogen eliminated to a level of above 80%. A raw POME can remove up to 70% of the phosphorus, compared to a sterilised POME's 10% removal. The sterilised POME had no bacteria, which accounted for the 60% difference in phosphorus removal effectiveness. Wastewater from the preparation of botanical food is the most environmentally benign and can be used as biofuel, fertiliser, and animal feed. Essential minerals like Fe, K, and N were abundant in the *P. purpureum* biomass that thrived in POME. These are essential nutrients for the growth of plants. This biomass could therefore be converted into biofertilizer [145]. Study by Okurowska *et al.* [146] on the leachate collected from a landfill in Chesterfield, UK showed that by using *C. vulgaris* with *Nitrosomonas* the removal efficiency of N-NH_3 and $\text{PO}_4^{3-}\text{-P}$ were 99% and 100% respectively. In another study Nair and Nagendra [147] reported that in the treatment of leachate collected from a landfill in Chennai, India using *C. pyrenoidosa* with nitrogen fixing bacteria reduced TN and $\text{PO}_4^{3-}\text{-P}$ up to 70% and 89%, respectively.

The removal of nitrogen (40–50 mg/L $\text{NH}_4^+\text{-N}$) achieved by microalgae-bacteria consortium was 99% as compared to 58% pure, microalgae treatment [148]. Likewise in the treatment of phosphorus (60 mg/L $\text{PO}_4^{3-}\text{-P}$) the microalgae-bacteria consortium removed 70% as compared to 10% made by pure microalgae treatment. Furthermore, the productivity of biomass was 4-fold with microalgae-bacteria as compared to 2-fold with pure microalgae treatment. Even the lipid accumulation was 42% that was considerable high with microalgae-bacteria treatment as compared to 17% with pure microalgal treatment [149]. Table 10 [150–161] illustrates the removal efficiency of various microalgal strains that are cultivated into different types of wastewaters.

The municipal, industrial, and agricultural wastewater sources can all be treated by the algae WWT facility of Algal Enterprises (Australia). In a closed PBR system, local algae species employ photosynthetically active radiation as their primary energy source. The generated algal biomass is co-digested anaerobically to produce a methane-rich biogas that is then used to generate energy [162]. The RNEW® approach of Microbio Engineering (US) treats N and P-rich municipal wastewater to produce feedstock biomass for biofuel production using mechanically mixed, CO_2 -gassed open raceway ponds [163]. The Advanced Integrated Wastewater Pond System (AIWPS®), also known as Energy Ponds, was created by Oswald Green Technologies to remove both pollutants from wastewater from industrial, agricultural, and municipal sources. First, wastewater solids are removed using anaerobic ponds or gravity settlers. Next, microalgae in high-rate algae ponds assimilate the removed organic and inorganic substances. The Energy Ponds harvested algal biomass is used to make fertiliser, animal feed, and raw materials for polymers and biodiesel [164]. Algae Systems, LLC provides a different strategy. A low-cost offshore floating PBR system has been created by this US corporation and is used in envi-

Table 10

Removal efficiency of various microalgae strains that are cultivated into different types of wastewaters.

Type of wastewater	Microalgae strain	Treatment efficiency (%)	Ref.
Textile	<i>Scenedesmus abundas</i>	COD: 86.67, N: 93, P: 90	[150]
	<i>Anabaena ambigua</i>	COD: 50, N: 52.95, P: 63.05	[150]
Municipal	<i>Chlorella zofingiensis</i>	COD: -, N: 93, P: 90	[151]
	<i>Scenedesmus obliquus</i>	COD: 99, N: 99, P: 100	[152]
Dairy	<i>Scenedesmus</i> sp.	COD: 90.5, N: 100, P: 91.24	[153]
	<i>ASK22</i>	COD: 98.4, N: 98.8, P: 100	[154]
	<i>Arthrospira platensis</i>	COD: 77, N: -, P: -	[155]
	<i>Spirulina</i> sp.	COD: 77, N: -, P: -	[155]
Swine/piggery	<i>Chlorella vulgaris</i>	COD: 52.5, N: 100, P: 68–74	[156]
	<i>Tribonema</i> sp.	COD: 52.5, N: 100, P: 68–74	[157]
	<i>Chlorella vulgaris</i>	COD: -, N: 100, P: 100	[158]
Domestic	<i>Scenedesmus</i> sp.	COD: -, N: 98.8, P: 97.7	[159]
Aquaculture	<i>Consortia-Euglena gracilis</i> , <i>Selenastrum</i>	COD: 56–58, N: 89, P: 84–96	[160]
	<i>Scenedesmus obliquus</i>	COD: -, N: 86.1, P: 82.7	[161]
Sewage treatment plant	<i>Scenedesmus</i> sp.	COD: 56–58, N: 5.84, P: 0.85 (mg L ⁻¹ d ⁻¹)	[161]

ronments with light and CO₂ conditions to absorb nutrients downstream from their source. The offshore PBR was shown to have removal efficiency of 75% (total N), 93% (total P), and 75% for 50,000 gal per day of raw municipal wastewater (BOD) [165].

6. Challenges and future prospects

The key challenge encountered in microalgal-biofuel production is the high cost in upstream and downstream processes. A study reported that during the production of 1 ton of *Chlorella vulgaris* the system could treat 1443 m³ of wastewater. The use of wastewater brought down the cost of biomass from \$809 to \$232 [166]. It was reported in a study that water footprint was 1700 m³/ton of the production of biodiesel when pond (~390 m³) and PBR (60 m³) are employed for the cultivation of microalgae. There is one common issue with POME and LL that they possess dark colour and bad odour which might be a challenge if the wastewaters are not pretreated and diluted as the colour can hinder the photosynthetic reactions. Bioremediation of POME and LL using microalgae is still at lab scale due to the cost of installing PBRs at the site because open systems are extremely susceptible to contamination. Therefore to begin with microalgal bioremediation can be implemented as one of the steps for pollutants removal and nutrients uptake. Jayakumar *et al.* [167] stated that removing the nutrients and water input can save about 2343 \$/ha to obtain 110 MT ha⁻¹ yr⁻¹ of microalgae. The total cost of raw materials is about 70% of the total cost involved in producing biodiesel. The savings obtained by utilizing water and nutrients from wastewater could go up to 7% of the total cost of biomass produced [168]. In microalgae cultivated in POME, both N and P degradation and microalgal growth is achieved simultaneously. Thus, reducing the extra cost of nutrients to be supplied for microalgae growth [169]. NASA gave the proposal for offshore membrane enclosures to cultivate

algae (OMEGA) with municipal wastewater in floating PBRs. New Zealand's Aquaflow Bionomic Corporation has also implemented microalgae technology for the treatment of wastewater. Microalgae that are cultivated in wastewater can accumulate biomass that are viable for extraction and conversion into numerous value-added bio-products and fuel bioproducts through downstream processing [136]. Several examples of biorefinery of biofuels are pyrolysis process produces biochar and biolysis as well as transesterification that generates biodiesel. Moreover, biomethane can be developed through anaerobic digestion and bio-oil could be formed via thermochemical derivation [161]. Bioremediation of heavy metals in wastewater will inevitably generate biomass since passive biosorption occurs during uptake process. One of fuel bioproducts, which is biochar, is an excellent toxic chemical (surfactants, antimicrobials, etc.) and dye adsorbent that are found in wastewater. Carbon footprint of wastewater treatment plant can be significantly decreased altogether with soil properties enhancement by the means of sludge-originated biochar application [138]. Therefore, there is an increasing trend in stabilizing microalgae-based biofuel production by improving the cultivation using wastewater [170]. Researchers also recommended that microalgae cultivation be co-located at the industrial plant site to fully utilize waste flue gas, wastewater, and waste nutrients, leading to the overall reduction of cost and environmental sustainability [166,171].

7. Conclusions

With the increasing demand of palm oil and increase in solid waste generation, the generation of POME and LL is increasing at an overwhelming rate, in Malaysia and other parts of the world. The existing treatment technologies are based on physical, chemical, and biological processes which are uneconomical, energy intensive, have high water and carbon footprint, and larger area requirement. Microalgae can contribute to the bioremediation of wastewaters, as the wastewater can serve the purpose of providing nutrients (orthophosphate and nitrate) for microalgal growth. Therefore, this review provides an insight of integrating microalgae cultivation with POME and LL to achieve the following objectives: (i) pollutants removal; (ii) nutrients uptake; (iii) CO₂ sequestration; (iv) production of rich biomass; (v) production of biofuels and other myriad products; and (vi) reduction of water footprint and cost of nutrients. Hence, it is important to integrate microalgae treatment in wastewaters and utilization of CO₂ for environmental protection, and microalgae valorization to produce renewable energies and other valuable products. This review reveals that the utilization of POME and LL to cultivate microalgae for biomass and biofuels is indeed an environmentally sustainable option. The bioremediation potential of microalgae in the treatment of POME and LL by the assimilation of nutrients (N and P), COD removal, and biomass production, are documented. The review gives a comprehensive account on how the bioremediation of POME and LL will contribute to circular bioeconomy by the simultaneous treatment of wastewaters and production of biomass, which can further be utilized for biofuels and bioproducts. The review also focusses on the SDGs benefited by the microalgal bioremediation of wastewaters.

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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References

- [1] A.F.M. Udaiyappan, H.A. Hasan, M.S. Takriff, et al., *J. Water Process Eng.* 35 (2020) 101203.
- [2] M.K. Lam, K.T. Lee, *Biotechnol. Adv.* 29 (2011) 124–141.
- [3] M.P.O. Board, Overview of the Malaysian Oil Palm Industry 2018, Malaysian Palm Oil Board, 2010.
- [4] W.Y. Cheah, P.L. Show, J.C. Juan, J.S. Chang, T.C. Ling, *Energy Convers. Manag.* 174 (2018) 430–438.
- [5] W.Y. Cheah, P.L. Show, J.C. Juan, J.S. Chang, T.C. Ling, *Energy Convers. Manag.* 164 (2018) 188–197.
- [6] W.Y. Cheah, P.L. Show, J.C. Juan, J.S. Chang, T.C. Ling, *Clean Technol. Environ. Policy*. 20 (2018) 2037–2045.
- [7] M.P.O. Board-MPOB, Overview of the Malaysian oil Palm Industry 2009, Ministry of Plantation Industries and Commodities, Malaysia, 2010.
- [8] H.Z. Nahrul, F.J. Nor, M. Ropandi, A. Astimar, *J. Oil Palm Res.* 29 (2017) 528–540.
- [9] K.S. Khoo, X. Tan, P.L. Show, et al., *Chem. Biochem. Eng. Q.* 34 (2020) 1–24.
- [10] B. Porto, A.L. Gonçalves, A.F. Esteves, et al., *Chem. Eng. J.* 413 (2021) 127546.
- [11] I. Ahmad, N. Abdullah, S. Chelliapan, et al., Effectiveness of Anaerobic Technologies in the Treatment of Landfill Leachate, in: strategies of Sustainable Solid Waste Management, IntechOpen (2020), doi:10.5772/intechopen.94741.
- [12] I. Ahmad, N. Abdullah, S. Chelliapan, et al., *Mater. Today: Proc.* 46 (2021) 1913–1921.
- [13] F.A. El-Gohary, G. Kamel, *Ecol. Eng.* 94 (2016) 268–274.
- [14] W.H. Leong, N.A.M. Saman, W. Kiatkittipong, et al., *Fuel* 313 (2022) 123052.
- [15] W.H. Leong, S.N.A. Zaine, Y.C. Ho, et al., *J. Environ. Manage.* 249 (2019) 109384.
- [16] S.N.H.A. Bakar, H.A. Hasan, A.W. Mohammad, et al., *J. Clean. Prod.* 171 (2018) 1532–1545.
- [17] Y.Y. Choong, K.W. Chou, I. Norli, *Renew. Sustain. Energy Rev.* 82 (2018) 2993–3006.
- [18] K.S. Khoo, W.Y. Chia, K.W. Chew, P.L. Show, *Indian J. Microbiol.* 61 (2021) 262–269.
- [19] A.T. Nair, J. Senthilnathan, S.S. Nagendra, *J. Water Process Eng.* 28 (2019) 322–330.
- [20] I. Dogaris, E. Ammar, G.P. Philippidis, *World J. Microbiol. Biotechnol.* 36 (2020) 1–25.
- [21] I. Ahmad, S. Chelliapan, N. Othman, N.S. Nasri, S. Krishnan, *Desalin. Water Treat.* 183 (2020) 268–275.
- [22] M. Lippi, M.B.R.G. Ley, G.P. Mendez, R.A.F.C. Junior, *Ciência e Natura* 40 (2018) 78.
- [23] T.A. Kurniawan, W.H. Lo, G.Y. Chan, *J. Hazardous Mater.* 129 (2006) 80–100.
- [24] A.P. Peter, K.S. Khoo, K.W. Chew, et al., *Environ. Chem. Lett.* 19 (2021) 2891–2904.
- [25] S.S. Chan, K.S. Khoo, K.W. Chew, T.C. Ling, P.L. Show, *Bioresour. Technol.* 344 (2022) 126159.
- [26] N.S.M. Aron, K.S. Khoo, K.W. Chew, et al., *J. Water Process Eng.* 39 (2021) 101701.
- [27] I. Ahmad, N. Abdullah, I. Koji, A. Yuzir, S. Mohamad, *Bull. Chem. React. Eng. Catal.* 16 (2021) 413–429.
- [28] Y.K. Choi, H.M. Jang, E. Kan, *Biotechnol. Bioprocess Eng.* 23 (2018) 333–340.
- [29] Q. Emparan, Y.S. Jye, M.K. Danquah, R. Harun, *J. Water Process Eng.* 33 (2020) 101043.
- [30] F. Ghazal, E. Mahdy, M. El-Fattah, et al., *Nat. Sci.* 16 (2018) 98–104.
- [31] S. Henkanatte-Gedera, T. Selvaratnam, M. Karbakhshvari, et al., *Algal Res.* 24 (2017) 450–456.
- [32] D. Tchinda, S. Henkanatte-Gedera, I. Abeyisiriwardana-Arachchige, et al., *Algal Res.* 42 (2019) 101578.
- [33] H.B. Hariz, M.S. Takriff, N.H.M. Yasin, M.M. Ba-Abbad, N.I.N.M. Hakimi, *J. Water Process Eng.* 32 (2019) 100907.
- [34] I. Dogaris, B. Loya, J. Cox, G. Philippidis, *Bioresour. Technol.* 282 (2019) 18–27.
- [35] I. Ahmad, A. Yuzir, S. Mohamad, K. Iwamoto, N. Abdullah, Role of Microalgae in Sustainable Energy and Environment, in: 2021 IOP Conf. Ser.: Mater. Sci. and Eng., IOP Publishing, vol. 1051, 012059.
- [36] J.W.R. Chong, K.S. Khoo, G.Y. Yew, et al., *Bioresour. Technol.* 342 (2021) 125947.
- [37] N. Abdullah, A. Yuzir, T.P. Curtis, A. Yahya, Z. Ujang, *Bioresour. Technol.* 127 (2013) 181–187.
- [38] T.E. Seiple, A.M. Coleman, R.L. Skaggs, *J. Environ. Manage.* 197 (2017) 673–680.
- [39] S.F. Mohsenpour, S. Hennige, N. Willoughby, A. Adeyoye, T. Gutierrez, *Sci. Total Environ.* 752 (2021) 142168.
- [40] B. Porto, A.L. Gonçalves, A.F. Esteves, et al., *Chem. Eng. J.* 413 (2021) 127546.
- [41] C. Viegas, C. Nobre, A. Mota, et al., *J. Environ. Chem. Eng.* 9 (2021) 105187.
- [42] A.L.P. Paiva, D.G. da Fonseca Silva, E. Couto, *J. Environ. Chem. Eng.* 9 (2021) 105952.
- [43] M. Martínez-Ruiz, A. Molina-Vázquez, B. Santiesteban-Romero, et al., *Environ. Pollut.* 306 (2022) 119422.
- [44] D. Hu, J. Zhang, R. Chu, et al., *Bioresour. Technol.* 342 (2021) 126003.
- [45] L. de Souza, A.S. Lima, Â.P. Matos, et al., *J. Clean. Prod.* 303 (2021) 127094.
- [46] J.S.R. Fernando, M. Premaratne, D.M.S.D. Dinalankara, G.L.N.J. Perera, T.U. Ariyadasa, *J. Environ. Chem. Eng.* 9 (2021) 105375.
- [47] A. Karim, M.A. Islam, Z.B. Khalid, et al., *Renew. Energy* 176 (2021) 106–114.
- [48] A.F.M. Udaiyappan, H.A. Hasan, M.S. Takriff, et al., *J. Clean. Prod.* 294 (2021) 126295.
- [49] W.Y. Chia, Y.Y. Chong, K.W. Chew, et al., *J. Environ. Chem. Eng.* 8 (2020) 104519.
- [50] K.S. Khoo, K.W. Chew, G.Y. Yew, et al., *Bioresour. Technol.* 304 (2020) 122996.
- [51] N.S. Mat Aron, K.S. Khoo, K.W. Chew, et al., *Int. J. Energy Res.* 44 (2020) 9266–9282.
- [52] H.R. Lim, K.S. Khoo, K.W. Chew, et al., *Environ. Pollut.* 284 (2021) 117492.
- [53] J.Y. Yong, K.W. Chew, K.S. Khoo, P.L. Show, J.S. Chang, *Biotechnol. Adv.* 47 (2021) 107684.
- [54] K.W. Chew, K.S. Khoo, H.T. Foo, et al., *Chemosphere* 268 (2021) 129322.
- [55] J. Xu, X. Fan, X. Zhang, et al., *PLoS One* 7 (2012) e37438.
- [56] R. Whittom, A. Le Mével, M. Pidou, et al., *Water Res.* 91 (2016) 371–378.
- [57] R.S. Al-Zuhairi, S. Surkatti, *Environ. Sci. Pollut. Res.* 25 (2018) 33936–33956.
- [58] S. Perumal, A. Thirunavukkarasu, P. Pachappan, *Advances in Marine and Brackishwater Aquaculture*, 1st ed., Springer, New Delhi, 2015.
- [59] S. Shah, A. Ahmad, M. Othman, M. Abdullah, *Int. J. Green Energy* 13 (2016) 200–207.
- [60] H. Kamyab, M.F.M. Din, A. Keyvanfar, et al., *Energy Procedia* 75 (2015) 2400–2408.
- [61] H. Kamyab, M.F. Md Din, C.T. Lee, et al., *Desalin. Water Treat.* 55 (2015) 3737–3749.
- [62] M.A. Nur, G. Garcia, P. Boelen, A.G. Buma, *J. Appl. Phycol.* 33 (2021) 901–915.
- [63] Y. Li, M. Horsman, B. Wang, N. Wu, C.Q. Lan, *Appl. Microbiol. Biotechnol.* 81 (2008) 629–636.
- [64] J. Gao, V. Oloibiri, M. Chys, et al., *Rev. Environ. Sci. Biotechnol.* 14 (2015) 93–122.
- [65] Q. Liao, H.X. Chang, Q. Fu, et al., *Bioresour. Technol.* 250 (2018) 583–590.
- [66] W.Y. Cheah, P.L. Show, J.S. Chang, T.C. Ling, J.C. Juan, *Bioresour. Technol.* 184 (2015) 190–201.
- [67] C. Mukherjee, R. Chowdhury, T. Sutradhar, et al., *Algal Res.* 19 (2016) 225–236.
- [68] H.J. Choi, S.M. Lee, *Environ. Eng. Res.* 18 (2013) 235–239.
- [69] Y. Yang, X. Shi, W. Ballent, B.K. Mayer, *Water Environ. Res.* 89 (2017) 2122–2135.
- [70] N. Powell, A.N. Shilton, S. Pratt, Y. Chisti, *Environ. Sci. Technol.* 42 (2008) 5958–5962.
- [71] S. Ota, M. Yoshihara, T. Yamazaki, et al., *Sci. Rep.* 6 (2016) 1–11.
- [72] S.T. Dyhrma, Nutrients and their acquisition: phosphorus physiology in microalgae, in: The physiology of microalgae, Springer, Cham, 2016, pp. 155–183.
- [73] F.F. Chu, P.N. Chu, P.J. Cai, et al., *Bioresour. Technol.* 134 (2013) 341–346.
- [74] Z.T. Khanzada, *Biotechnol. Rep.* 25 (2020) e00419.
- [75] G.M. Tian, H.X. Cheng, Preliminary evaluation of a newly isolated microalga *Scenedesmus* sp. CHX1 for treating landfill leachate, in: Third International Conference on Intelligent System Design and Engineering Applications, 2013, pp. 1057–1060.
- [76] E.M. Mustafa, S.M. Phang, W.L. Chu, *J. Appl. Phycol.* 24 (2012) 953–963.
- [77] A. Paskuliakova, S. Tonry, N. Touzet, *Water Res.* 99 (2016) 180–187.
- [78] A. Paskuliakova, T. McGowan, S. Tonry, N. Touzet, *Ecotoxicol. Environ. Saf.* 147 (2018) 622–630.
- [79] S.F. Pereira, A.L. Gonçalves, F.C. Moreira, et al., *Int. J. Mol. Sci.* 17 (2016) 1926.
- [80] L. Lin, G. Chan, B. Jiang, C. Lan, *Waste Manag.* 27 (2007) 1376–1382.
- [81] C.L. Martins, H. Fernandes, R.H. Costa, *Bioresour. Technol.* 147 (2013) 562–568.
- [82] X. Zhao, Y. Zhou, S. Huang, et al., *Bioresour. Technol.* 156 (2014) 322–328.
- [83] M. El Ouaer, A. Kallel, M. Kasmi, A. Hassen, I. Trabelsi, *Arab. J. Geosci.* 10 (2017) 1–9.
- [84] N. Bordoloi, J. Tiwari, S. Kumar, J. Korstad, K. Baudh, Efficiency of algae for heavy metal removal, bioenergy production, and carbon sequestration, in: Emerging Eco-friendly Green Technologies for Wastewater Treatment, Springer, Singapore, 2020, pp. 77–101.
- [85] K.A. Salam, *Biofuel Res. J.* 6 (2019) 948.
- [86] M. Chugh, L. Kumar, D. Bhardwaj, N. Bharadvaja, Bioaccumulation and detoxification of heavy metals: an insight into the mechanism, in: Development in Wastewater Treatment Research and Processes, Elsevier, 2022, pp. 243–264.
- [87] R.A. Dar, N. Sharma, K. Kaur, U.G. Phutela, Feasibility of microalgal technologies in pathogen removal from wastewater, in: Application of Microalgae in Wastewater Treatment, Springer, Cham, 2019, pp. 237–268.
- [88] M. Mezzari, J. Prandini, J.D. Kich, M.B. da Silva, *J. Bioremediat. Biodegrad.* 8 (2017) 1000379.
- [89] E. Ardal, Phycoremediation of Pesticides Using Microalgae, Swedish University of Agricultural Sciences, Master's Thesis, 2014, pp. 1–40.
- [90] L. Brennan, P. Owende, *Renew. Sustain. Energy Rev.* 14 (2010) 557–577.
- [91] I. Ahmad, N. Abdullah, I. Koji, A. Yuzir, S.E. Muhammad, Evolution of Photobioreactors: a Review based on Microalgal Perspective, in: 2021 IOP Conf. Ser.: Mater. Sci. and Eng., IOP Publishing, vol. 1142, 012004.
- [92] P.M. Schenk, S.R. Thomas-Hall, E. Stephens, et al., *Bioenergy Res.* 1 (2008) 20–43.

- [93] M.K. Lam, K.T. Lee, A.R. Mohamed, *Biofuels, Bioprod. Biorefin.* 3 (2009) 601–612.
- [94] S. Vijaya, M. Ngan, C. May, M. Nik, *Am. J. Environ. Sci.* 4 (2008) 310–315.
- [95] D.L. Sutherland, C. Howard-Williams, M.H. Turnbull, P.A. Broady, R.J. Craggs, *Bioresour. Technol.* 184 (2015) 222–229.
- [96] A.A. Casazza, M. Rovatti, *Desalin. Water Treat.* 127 (2018) 71–74.
- [97] H. Chang, Q. Fu, N. Zhong, et al., *Bioresour. Technol.* 277 (2019) 18–26.
- [98] W.Y. Cheah, P.L. Show, Y.J. Yap, et al., *Bioengineered* 11 (2020) 61–69.
- [99] D.Y.Y. Tang, K.S. Khoo, K.W. Chew, et al., *Bioresour. Technol.* 304 (2020) 122997.
- [100] Z. Rasouli, B. Valverde-Pérez, M. D'Este, D. De Francisci, I. Angelidaki, *Biochem. Eng. J.* 134 (2018) 129–135.
- [101] H. Chang, X. Quan, N. Zhong, et al., *Bioresour. Technol.* 266 (2018) 374–381.
- [102] A. Hernández-García, S.B. Velásquez-Orta, E. Novelo, et al., *Ecotoxicol. Environ. Saf.* 174 (2019) 435–444.
- [103] H.O. Tighiri, E.A. Erkurt, *Bioresour. Technol.* 286 (2019) 121396.
- [104] T. Mahlia, M. Abdulmuin, T. Alamsyah, D. Mukhlisien, *Energy Convers. Manag.* 42 (2001) 2109–2118.
- [105] S.A. Khan, M.Z. Hussain, S. Prasad, U. Banerjee, *Renew. Sust. Energ. Rev.* 139 (2009) 2361–2372.
- [106] S. Li, X. Li, S.H. Ho, *Chemosphere* (2021) 132863.
- [107] G.G. Satpati, R. Pal, *Photosynthesis in algae*, in: *Applied Algal Biotechnology, Recent Trends in Biotechnology*, Nova Science Publishers Incorporated, 2020.
- [108] C. Yoo, S.Y. Jun, J.Y. Lee, C.Y. Ahn, H.M. Oh, *Bioresour. Technol.* 101 (2010) S71–S74.
- [109] M.M.A. Nur, A.G. Buma, *Waste Biomass Valori.* 10 (2019) 2079–2097.
- [110] S. Sapie, S. Jumali, S. Mustaffa, D. Pebrian, *Analysis of POME Discharge Quality from Different Mill in Perak, Malaysia: a case study*, in: 2019 IOP Conf. Ser.: *Earth and Environ. Sci.*, IOP Publishing, vol. 327, 012022.
- [111] K. Rambabu, A. Thanigaivelan, G. Bharath, et al., *Chemosphere* 268 (2021) 128809.
- [112] K.S. Khoo, S.Y. Lee, C.W. Ooi, et al., *Bioresour. Technol.* 288 (2019) 121606.
- [113] M. Giampietro, *Ecol. Econ.* 162 (2019) 143–156.
- [114] I. Ahmad, N. Abdullah, K. Iwamoto, A. Yuzir, *Chem. Eng. Trans.* 89 (2021) 391–396.
- [115] Y. Torres-Tijji, F.J. Fields, S.P. Mayfield, *Biotechnol. Adv.* 41 (2020) 107536.
- [116] Z. Gojkovic, R.H. Lindberg, M. Tysklind, C. Funk, *Ecotoxicol. Environ. Saf.* 170 (2019) 644–656.
- [117] H. Chowdhury, B. Loganathan, *Curr. Opin. Green Sustain. Chem.* 20 (2019) 39–44.
- [118] S. Price, U. Kuzhiumparambil, M. Pernice, P.J. Ralph, *J. Environ. Chem. Eng.* 8 (2020) 104007.
- [119] D. Calahan, D. Biersch, W. Adey, *Ecol. Eng.* 85 (2015) 275–282.
- [120] P. Chiaiese, G. Corrado, G. Colla, M.C. Kyriacou, Y. Roupheal, *Front. Plant Sci.* 9 (2018) 1782.
- [121] H. Karan, C. Funk, M. Grabert, M. Oey, B. Hankamer, *Trends Plant Sci.* 24 (2019) 237–249.
- [122] J. Yarnold, H. Karan, M. Oey, B. Hankamer, *Trends Plant Sci.* 24 (2019) 959–970.
- [123] W.Y. Chia, D.Y.Y. Tang, K.S. Khoo, A.N.K. Lup, K.W. Chew, *Environ. Sci. Ecotechnol.* 4 (2020) 100065.
- [124] W.Y. Cheah, T.C. Ling, P.L. Show, et al., *Appl. Energy* 179 (2016) 609–625.
- [125] N.A. Idris, S.K. Loh, H.L.N. Lau, et al., *J. Oil Palm Res.* 29 (2017) 291–299.
- [126] N.A. Osman, F.A. Ujang, A.M. Roslan, M.F. Ibrahim, M.A. Hassan, *Sci. Rep.* 10 (2020) 1–10.
- [127] R. Serena, B. Filippo, S. Marinello, *Life cycle assessment of a biofuel production system from algal biomass cultivated in photobioreactors*, in: 28th European Biomass Conference and Exhibition, ETA-Florence Renewable Energies, 2020, pp. 837–844.
- [128] M.A. Nur, *World Appl. Sci. J.* 31 (2014) 959–967.
- [129] M.A. Nur, H. Hadiyanto, *J. Eng. Technol. Sci.* 4 (2015) 487–497.
- [130] E.V. Putri, M.F.M. Din, Z. Ahmed, H. Jamaluddin, S. Chelliapan, *Investigation of microalgae for high lipid content using palm oil mill effluent (POME) as carbon source*, in: *International conference on environment and industrial innovation*, 12, IPCBEE, 2011, pp. 85–89.
- [131] N. Selmani, M.E. Mirghani, M.Z. Alam, *Study the growth of microalgae in palm oil mill effluent waste water*, in: 2013 IOP Conf. Ser.: *Earth and Environ. Sci.*, IOP Publishing, vol. 16, 012006.
- [132] S. Dawood, M. Ahmad, M. Zafar, et al., *Chemosphere* 291 (2022) 132780.
- [133] M.K. Lam, K.T. Lee, A.R. Mohamed, *Biotechnol. Adv.* 28 (2010) 500–518.
- [134] S. Nawaz, M. Ahmad, S. Asif, et al., *Bioresour. Technol.* 343 (2022) 126068.
- [135] R. Harun, M. Singh, G.M. Forde, M.K. Danquah, *Renew. Sust. Energ. Rev.* 14 (2010) 1037–1047.
- [136] K.W. Chew, J.Y. Yap, P.L. Show, et al., *Bioresour. Technol.* 229 (2017) 53–62.
- [137] A. Ahmad, F. Banat, H. Alsafar, S.W. Hasan, *Sci. Total Environ.* 806 (2022) 150585.
- [138] W.S. Chai, W.G. Tan, H.S.H. Munawaroh, et al., *Environ. Pollut.* 269 (2021) 116236.
- [139] W.L. Chu, S.M. Phang, *Biosorption of heavy metals and dyes from industrial effluents by microalgae*, in: *Microalgae Biotechnology for Development of Biofuel and Wastewater Treatment*, Springer, Singapore, 2019, pp. 599–634.
- [140] S.D. Kumar, P. Santhanam, R. Nandakumar, et al., *Afr. J. Biotechnol.* 13 (2014).
- [141] H.E.S. Toulabah, M.M. El-Sheekh, M.M. Ismail, H. El-Kassas, *Molecules* 27 (2022) 1141.
- [142] R. Kalra, S. Gaur, M. Goel, *J. Water Process Eng.* 40 (2021) 101794.
- [143] A. Fallahi, F. Rezvani, H. Asgharnejad, et al., *Chemosphere* 272 (2021) 129878.
- [144] C. Zhang, S.H. Ho, A. Li, L. Fu, D. Zhou, *J. Water Process Eng.* 39 (2021) 101739.
- [145] W. Qu, C. Zhang, X. Chen, S.H. Ho, *J. Hazard. Mater.* 418 (2021) 126264.
- [146] K. Okurowska, E. Karunakaran, A. Al-Farttoosy, N. Couto, J. Pandhal, *Bioresour. Technol.* 319 (2021) 124246.
- [147] A.T. Nair, S. Nagendra, *Chlorella Pyrenoidosa mediated phycoremediation of landfill leachate*, in: *International Conference Impact of Global Atmospheric Changes on Natural Resources*, 2018, pp. 65–68.
- [148] Y. Gou, J. Yang, F. Fang, J. Guo, H. Ma, *Environ. Technol.* 41 (2020) 400–410.
- [149] T. Biswas, S. Bhushan, S.K. Prajapati, S.R. Chaudhuri, *J. Environ. Manage.* 286 (2021) 112196.
- [150] A. Brar, M. Kumar, V. Vivekanand, N. Pareek, *Int. J. Environ. Sci. Technol.* 16 (2019) 7757–7768.
- [151] W. Zhou, Z. Wang, J. Xu, L. Ma, *J. Biosci. Bioeng.* 126 (2018) 644–648.
- [152] A. Pandey, S. Srivastava, S. Kumar, *Biomass Bioenerg.* 128 (2019) 105319.
- [153] A. Pandey, S. Srivastava, S. Kumar, *Bioresour. Technol.* 293 (2019) 121998.
- [154] S. Hena, H. Znad, K. Heong, S. Judd, *Water Res.* 128 (2018) 267–277.
- [155] Q. Emparan, R. Harun, M. Danquah, *Appl. Ecol. Environ. Res.* 17 (2019) 889–915.
- [156] H.J. Choi, *Environ. Eng. Res.* 21 (2016) 393–400.
- [157] S. Huo, J. Liu, F. Zhu, et al., *Bioresour. Technol.* 314 (2020) 123718.
- [158] B. Molinuevo-Salces, A. Mahdy, M. Ballesteros, C. González-Fernández, *Renew. Energ.* 96 (2016) 1103–1110.
- [159] H.Y. Ren, J.N. Zhu, F. Kong, et al., *Energy Convers. Manag.* 180 (2019) 680–688.
- [160] M. Tossavainen, K. Lahti, M. Edelmann, et al., *J. Appl. Phycol.* 31 (2019) 1753–1763.
- [161] K.L. Yu, P.L. Show, H.C. Ong, et al., *Energy Convers. Manag.* 150 (2017) 1–13.
- [162] M. Montingelli, S. Tedesco, A. Olabi, *Renew. Sust. Energ. Rev.* 43 (2015) 961–972.
- [163] F. Wollmann, S. Dietze, J.U. Ackermann, et al., *Eng. Life Sci.* 19 (2019) 860–871.
- [164] Y. Nurdogan, W.J. Oswald, *Water Sci. Technol.* 31 (1995) 33–43.
- [165] F. Green, T. Lundquist, N. Quinn, et al., *Water Sci. Technol.* 48 (2003) 299–305.
- [166] L. Moreno-García, K. Adjallé, S. Barnabé, G. Raghavan, *Renew. Sust. Energ. Rev.* 76 (2017) 493–506.
- [167] S. Jayakumar, M.M. Yusoff, M.H.A. Rahim, G.P. Maniam, N. Govindan, *Renew. Sust. Energ. Rev.* 72 (2017) 33–47.
- [168] J. Van Wagenen, M.L. Pape, I. Angelidaki, *Water Res.* 75 (2015) 301–311.
- [169] A. Beuckels, E. Smolders, K. Muylaert, *Water Res.* 77 (2015) 98–106.
- [170] Y. Su, K. Song, P. Zhang, et al., *Renew. Sust. Energ. Rev.* 74 (2017) 402–411.
- [171] N.A. Sasongko, R. Noguchi, T. Ahamed, *Energy* 159 (2018) 1148–1160.