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Bulletin of Chemical Reaction Engineering & Catalysis, 16 (2) 2021, 413-429

Review Article

Potential of Microalgae in Bioremediation of Wastewater

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Received: 15th March 2021; Revised: 29th April 2021; Accepted: 29th April 2021
Available online: 4th May 2021; Published regularly: June 2021

Abstract

The increase in global pollution, industrialization and fast economic progress are considered to inflict serious consequences to the quality and availability of water throughout the world. Wastewater is generated from three major sources, *i.e.* industrial, agricultural, and municipal which contain pollutants, such as: xenobiotics, microplastics, heavy metals and augmented by high amount of carbon, phosphorus, and nitrogen compounds. Wastewater treatment is one of the most pressing issues since it cannot be achieved by any specific technology because of the varying nature and concentrations of pollutants and efficiency of the treatment technologies. The degradation capacity of these conventional treatment technologies is limited, especially regarding heavy metals, nutrients, and xenobiotics, steering the researchers to bioremediation using microalgae (Phycoremediation). Bioremediation can be defined as use of microalgae for removal or biotransformation of pollutants and CO_2 from wastewater with concomitant biomass production. However, the usage of wastewaters for the bulk cultivation of microalgae is advantageous for reducing carbon, nutrients cost, minimizing the consumption of freshwater, nitrogen, phosphorus recovery, and removal of other pollutants from wastewater and producing sufficient biomass for value addition for either biofuels or other value-added compounds. Several types of microalgae like *Chlorella* and *Dunaliella* have proved their applicability in the treatment of wastewaters. The bottlenecks concerning the microalgal wastewater bioremediation need to be identified and elucidated to proceed in bioremediation using microalgae. This objective of this paper is to provide an insight about the treatment of different wastewaters using microalgae and microalgal potential in the treatment of wastewaters containing heavy metals and emerging contaminants, with the specialized cultivation systems. This review also summarizes the end use applications of microalgal biomass which makes the bioremediation aspect more environmentally sustainable.

Keywords: Wastewater; microalgae; Bioremediation; photobioreactors; heavy metals; emerging contaminants

How to Cite: I. Ahmad, N. Abdullah, I. Koji, A. Yuzir, S.E. Mohamad (2021). Potential of Microalgae in Bioremediation of Wastewater. *Bulletin of Chemical Reaction Engineering & Catalysis*, 16(2), 413-429 (doi:10.9767/bcrec.16.2.10616.413-429)

Permalink/DOI: https://doi.org/10.9767/bcrec.16.2.10616.413-429

1. Introduction

The vitality water is well known throughout the world and the issue of sustainable water management is a critical issue of discussion in all the sections of society, but the water resources are still under the risk of either being depleted or polluted raising an alarming situation. The reasons behind this overwhelming condition are the tremendous increase in population, industrialization, urbanization and economic growth [1]. Pollution of surface or ground-

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water bodies or the mother environment is caused mainly by the human activities increasing the concentrations of the substances (natural or synthetic) above their prescribed limits which may cause harm to the humans and environment [2]. As a cross sectional element, it has been reported that around 80% of the rivers in China are already polluted by organic and/or inorganic substances as well as by heavy metals (HMs) and emerging contaminants (ECs) [3].

Wastewater is generated from three major sources *i.e.*, industrial, agricultural, and municipal which contain pollutants such as xenobiotics, microplastics, heavy metals and augmented by high amount of carbon, phosphorus, and nitrogen compounds. Wastewater treatment is one of the most pressing issues since it cannot be achieved by any specific technology because of the varying nature and concentrations of pollutants and efficiency of the treatment technologies [4,5]. The degradation capacity of these conventional treatment technologies is limited, especially regarding heavy metals, nutrients and xenobiotics causing accumulation of these substances in water bodies [6].

Intensified research led to the advent of microalgae because of its metabolic flexibility (can possess autotrophic, heterotrophic and mixotrophic metabolism) they can become a sustainable and efficient biological system for the treatment of various types of wastewater. Microalgae (Microphytes) are microscopic organisms either eukaryotic or prokaryotic in structure and are typically found in fresh or marine water bodies [7]. Microalgal photosynthesis includes light and dark reactions (Calvin cycle). Light reaction cycles occur in the thylakoids converting light energy to chemical energy, while in the dark cycle the active chemical energy is transformed to stable chemical energy. The process is depicted in Figure 1. The microalgae use CO_2 in the presence of light to produce energy. The overall photosynthetic reaction fixes CO_2 and produces glucose by synthesizing proteins, carbohydrates, and lipids (Equation (1)). 1.57 g of CO_2 is required to produce 1 g of glucose [8].

$$6CO_2 + 12H_2O + light + chlorophyl \rightarrow C_6H_{12}O_6 + 6CO_2 + 6H_2O \quad (1)$$

Thus, reduction in atmospheric CO_2 can be achieved by enhancing the photosynthetic efficiency of microalgae.

The fundamentals about the growth and trait of microalgae followed by their ad-

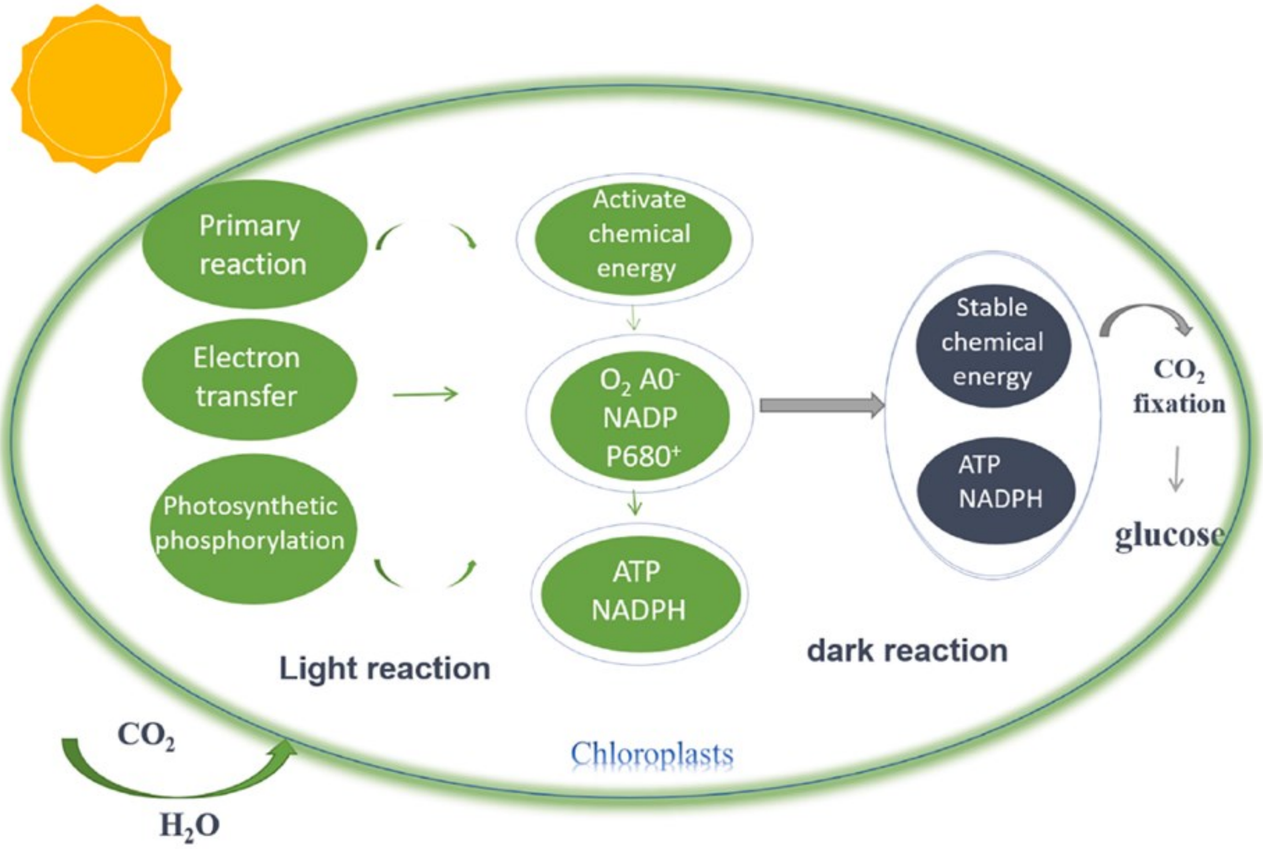
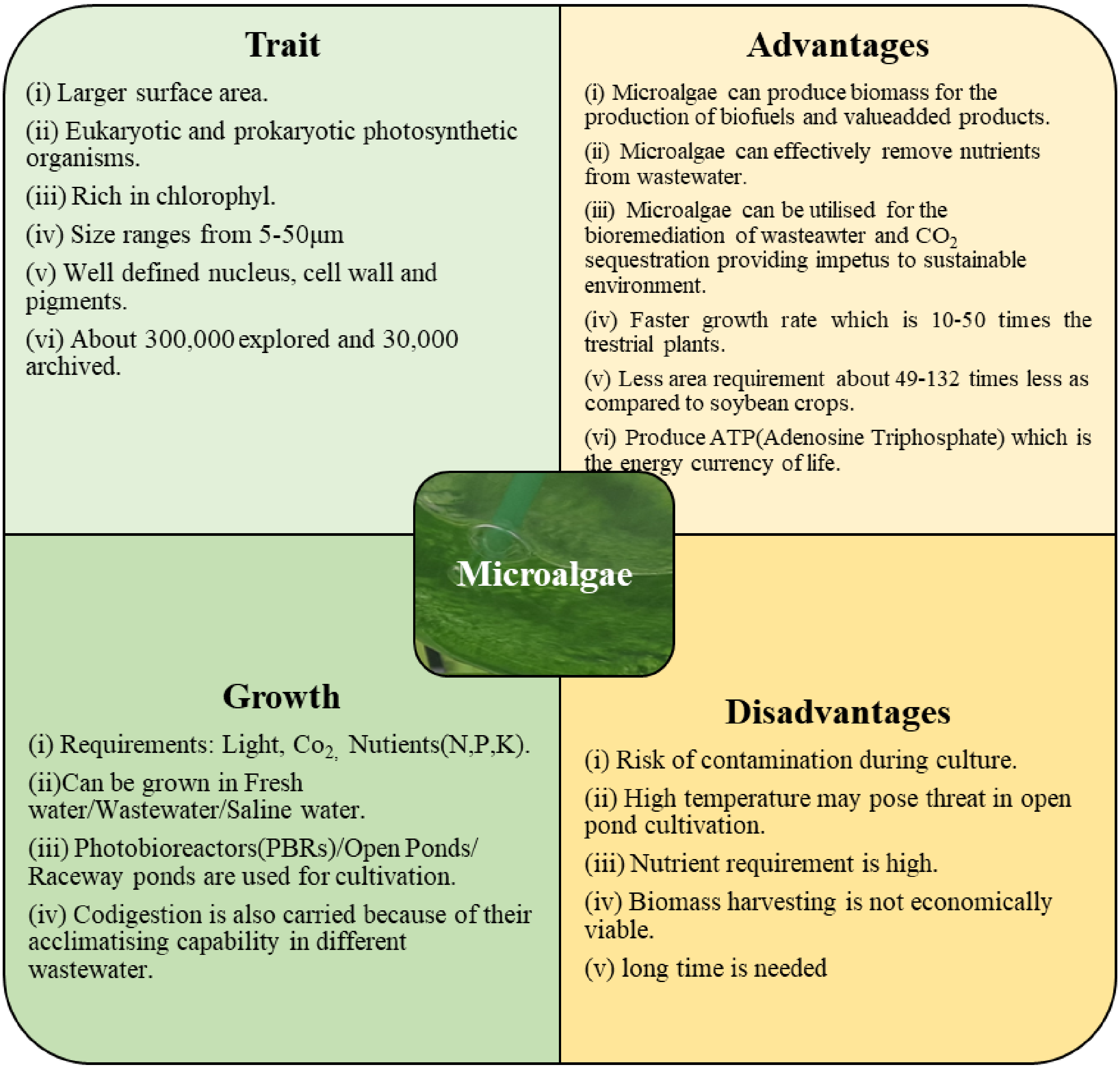


Figure 1. Microalgae photosynthesis reaction [9].

vantages and disadvantages can be understood from the illustration in Figure 2. Microalgae (green expedient) is considered as productive and potent in the treatment of various types of domestic and industrial wastewaters because of: (i) Less requirement of land, (ii) Low energy requirement, (iii) Less residual of organics/nutrients concentration, (iv) Sludge formation is lower as compared to aerobic treatment technologies, (v) Effectiveness in removing heavy metals (HMs) and emerging contaminants (ECs), (vi) The use of wastewater for the cultivation of microalgae can reduce drastically the fresh water requirement (by 90%), also supplementing the reduction in the cost of nutrients [10]. The history of using microalgal strains of *Chlorella* and *Dunaliella* for biomass production and wastewater treatment is known for more than 75 years [11].

The characteristics of wastewater is varying in terms of pH (2.0-8.0), temperature (>40 °C for fermentation residue from bioenergy industry, <10 °C for food processing industry) and organic load (>100 g/L for food processing industry) [12]. To handle such conditions specialized microalgal species are present which can act as extremophiles, *Galdieria sulphuraria* is having acidophilic nature (can tolerate pH down to 1.8) and temperature up to 56 °C and contain phycobiliprotein phycocyanin which is used as nutraceutical compound [13]. Therefore, its composition, acidic and thermophilic nature, and its metabolism make it a potential microalga in treating wastewater having high temperature, COD and low pH [14]. Still there exist many challenges in the wastewater treatment using microalgae, such as: (i) need for


Trait

(i) Larger surface area.

(ii) Eukaryotic and prokaryotic photosynthetic organisms.

(iii) Rich in chlorophyl.

(iv) Size ranges from 5-50µm

(v) Well defined nucleus, cell wall and pigments.

(vi) About 300,000 explored and 30,000 archived.

Advantages

(i) Microalgae can produce biomass for the production of biofuels and valueadded products.

(ii) Microalgae can effectively remove nutrients from wastewater.

(iii) Microalgae can be utilised for the bioremediation of wasteawter and CO_2 sequestration providing impetus to sustainable environment.

(iv) Faster growth rate which is 10-50 times the trestrial plants.

(v) Less area requirement about 49-132 times less as compared to soybean crops.

(vi) Produce ATP(Adenosine Triphosphate) which is the energy currency of life.

Growth

(i) Requirements: Light, Co_2, Nutients(N,P,K).

(ii)Can be grown in Fresh water/Wastewater/Saline water.

(iii) Photobioreactors(PBRs)/Open Ponds/ Raceway ponds are used for cultivation.

(iv) Codigestion is also carried because of their acclimatising capability in different wastewater.

Disadvantages

(i) Risk of contamination during culture.

(ii) High temperature may pose threat in open pond cultivation.

(iii) Nutrient requirement is high.

(iv) Biomass harvesting is not economically viable.

(v) long time is needed

Figure 2. Fundamentals of microalgae.

pre-treatment/dilution, (ii) imbalance in nutrients and wastewater composition, (iii) presence of inhibiting compounds and susceptibility to contamination, (iv) harvesting is sometimes uneconomic, and (v) low purity and productivity of biomass [15]. The process of bioremediation of wastewater using microalgae is depicted in Figure 3.

Bioremediation can be defined as use of microalgae for the treatment or biotransformation of nutrients/pollutants and CO_2 present in wastewaters with the concomitant production of biomass. This mini review summarizes the nutrient removal capability and the removal of various pollutants including heavy metals (HMs) and emerging contaminants (ECs) by

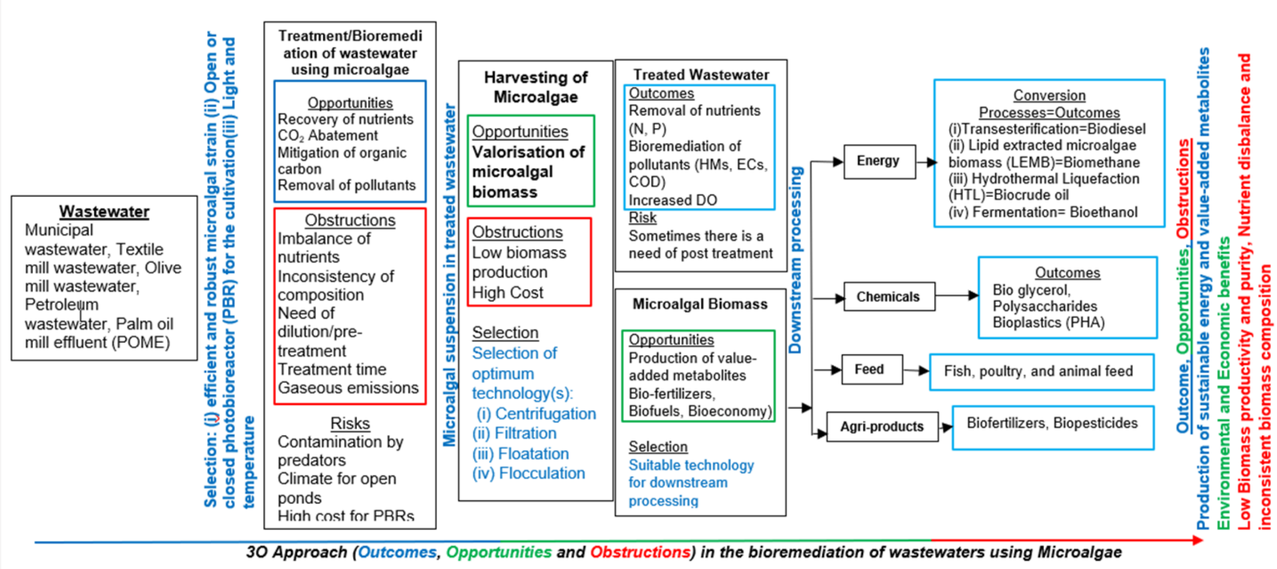


Figure 3. Approach of wastewater bioremediation using microalgae.

Table 1. Microalgal bioremediation of wastewaters

No.	Case Studies of Bioremediation	Location	Ref.
1	The use of *Chlorella vulgaris* obtained from Malaya Algae Culture collection for bioremediation of textile wastewater collected from Senawang Industrial Estate, Negeri Sembilan.	Kuala Lumpur, Malaysia	[16]
2	Treatment of fish processing wastewater using *Oocystis sp.* ;experimentally using Photobioreactors	Valladolid, Spain	[17]
3	Domestic wastewater bioremediation using microalgae *Chlorella vulgaris* and *Scenedesmus quadricauda* for physiochemical reduction.	Pune, India	[18]
4	Application of *Chlorella vulgaris* for reduction of organic and inorganic pollutant in sewage treatment plant wastewater.	Kombolcha, Ethiopia	[19]
5	Piggery wastewater treatment using isolated *Scenedesmus obliquus* obtained from municipal wastewater effluent.	Wonju, South Korea	[20]
6	Phycoremediation of sewage drainage using *Chlorella vulgaris*, *Rhizoclonium hieroglyphocum* and mixed algal cultures.	Lahore, Pakistan	[21]
7	Growth of *Botryococcus braunii* using urban wastewater from secondary treatment plant for bioremediation purpose.	Jaen, Spain	[22]
8	Application of bioremediation technique using Chlorella vulgaris, *Synechocystis salina* and *Gloeocapsa gelatinosa* in industrial polluted water.	Kerala, India	[23]
9	Application of microalgal bacterial flocs for industrial wastewater treatment using sequencing batch reactors.	Ghent, Belgium	[24]
10	Phycoremediation of greywater and dairy wastewater by *Botryococcus sp.* for physiochemical parameters removal.	Johor, Malaysia	[25]

using bioremediation of microalgae. The applications of some specialized photobioreactors in the treatment of wastewaters using microalgae are also incorporated. Previous review studies have focused more on the biorefinery aspects of microalgae and the open and closed systems used for the cultivation of microalgae. This study intends to elaborate the potential of microalgae in the treatment of various wastewater together with the efficacy of suspended and immobilized systems. The study gives an insight to the dual mode of Bioremediation, *i.e.* wastewater treatment and biomass production. The biomass is further processed to obtain biofuels and other value-added products is also discussed in the last section.

2. Bioremediation of Wastewater using Microalgae

Microalgae based wastewater treatment (MBWT) is considered as one of the most convincing technologies because of the potential of microalgae in the removal of pollutants and nutrients. MBWT is having various advantages like: (i) Bioremediation of wastewater (removal wastewater pollutants: COD, HMs, ECs); (ii) Nutrient's removal and recovery (*e.g.* Total Nitrogen (TN), Total Phosphorus (TP)); (iii) Recovery of water and reusability of culture medium. Different case studies utilizing microalgae for the bioremediation of wastewaters are summarized in Table 1.

2.1 Microalgae for the Treatment of Different Types of Wastewaters

Microalgae possess numerous advantages such as its adaptability with varying climatic conditions as well as varying nature of wastewater, removal of exclusive contaminants like polycyclic aromatic hydrocarbons (PAHs), pesticides, endocrine disrupting compounds (EDCs), *etc.*, high growth rates and valorization of microalgal biomass for biofuels and value-added products [26–28]. Since the microalgae are mostly photosynthetic in nature some exclusive genera of microalgae can utilize different types of organic matter in heterotrophic and mixotrophic modes subsequently reducing the BOD/COD of the wastewaters. Other than the bioaccumulation potential, microalgae (monoculture/consortia) can also convert / degrade organic pollutants (pesticides, phenolics, petroleum hydrocarbons) to less/no toxic compounds [29]. This assists in the cultivation of microalgae in organic rich wastewaters having high values of COD and also enhance the biomass and lipid yield [30]. The organic removal is shown in Figure 4, while the efficacy of microalgae in the removal of COD is shown in Table 2.

MWE treatment with microalgae shows good results in the removal of N and P, increase the DO content in the effluent and checks the growth of bacteria [34]. A twin layer

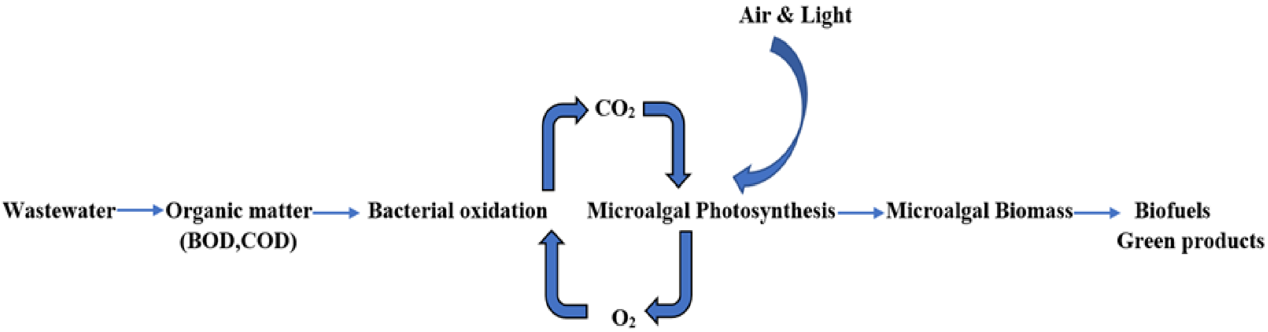


Figure 4. Organic removal taking place through photosynthetic oxygenation by microalgae.

Table 2. Effectiveness of microalgae in the removal of COD in wastewater.

Microalgal Species	Parameter	Removal performance	Ref.
Chlorella vulgaris	Chemical Oxygen Demand (COD)	93%	[27]
Chlorella sorokiniana	Soluble Chemical Oxygen Demand (SCOD)	70%	[31]
Scenedesmus obliquus	COD	90.3%-95.2%	[32]
Spirulina platensis	COD	90.02%	[33]

PBR was used by Shi *et al.* [35] to immobilize *Halochlorella rubescens* for the treatment of municipal wastewater. The rate of removal was shown in Table 3. The concentrations were well under the prescribed standards of European waste framework directive.

POME (Palm oil mill effluent) usually consists of very high concentrations of BOD, COD, and organic of N and P. Hadiyanto *et al.* [36] practiced the treatment consisting of two-stages for the anaerobically treated POME. In the first stage the treatment was done using the aquatic plants (hyacinth and water lily) for a period of 3-8 days, while the second stage involved the treatment using *Arthrospira platensis* (rate of growth = 0.412/d) for 15 days. The biological treatment of Olive Mill Wastewater (OMW) is quite problematic because of its antibacterial and phytotoxic nature. Bioremediation of pre-treated OMW was evaluated by

Table 3. Effectiveness of microalgae in the treatment of different wastewater.

Type of wastewater	Cultivation conditions	Species of Microalgae	Pollutants / Nutrients Removal	Ref.
Municipal Wastewater	Twin layer Photobioreactor	*Halochlorella rubescens*	PO_4^--P=73.2%, NO_3^--N=83.2%	[35]
Municipal wastewater	Continuous cultivation (HRT 0.04-10 days)	*Scenedesmus sp.*	TN=36-95.3% TP=40-100%	[40]
POME	Anaerobically treated POME (15 days)	*Arthrospira platensis*	COD=50.8%, N=96.5% and P=85.9%	[36]
Olive mill wastewater	Physico- chemically pre-treated OMW	*Chlorella pyrenoidosa*	COD=1.4%, Phenolic Compound=8% and N=19.2%(supplemented)	[37]
Textile wastewater	High-rate algae ponds (HRAPs)	*Chlorella vulgaris*	NH_4-N=45%, PO_4-P=33%, COD=38-62% and Color=42-50%	[16]
Petroleum wastewater	Bioremediation (48 hours)	*Parachlorella kessleri*	BTEX=56-64%	[39]
Dairy wastewater	Incubation:10days 30°C, 80RPM	*Chlorella vulgaris*	BOD=85.6%, COD=80.62 TN=85.47, TP=65.96%	[41]
Aquaculture wastewater	Incubation:30 days	*Tetraselmis suecica*	TN=49.4%, TP=99%	[42]
Landfill leachate	------	*Acutodesmus obliqus*	TN=30%, TP=93%	[43]
Pharmaceutical wastewater	pH=7.5	*Chlorella sorokiniana*	TN=70%, TP=89%	[44]

Table 4. Effectiveness of Microalgae in the removal of ECs.

Species of Microalgae	Contaminant	Removal %	Ref.
Cymbella sp.	Naproxen	97.1	[45]
Scenedesmus obliquus	Diclofenac	79	[46]
Chlamydomonas sp.	17β-estradiol	93.9	[47]
Chlorella sorokiniana	Paracetamol	70	[48]
Chlorella PY-ZU1	Ethinylestradiol	94	[49]
Monoraphidium braunii	Bisphenol A	48	[50]
Chlorella pyrenoidosa	Phenol	77.2	[51]
Chlorella vulgaris	Diazinon	94	[52]
Desmodesmus sp.	Triclosan-phenol	92.9	[53]
Raphidocelis subcapitata	Diethylstilbestrol	71.8	[54]

Hodaifa *et al.* [37] using *Chlorella pyrenoidosa* and found that the treatment considerably supplemented the removal of phenolic compounds and N. Wastewater coming from textile industry is of varying composition (acidic to alkaline) also having high concentration of color which makes it red, purple, black, *etc.* [38]. Chlorella vulgaris was used by Lim *et al.* [16] for the bioremediation of textile wastewater in the high rate algae ponds (HRAPs). The results achieved are shown in the Table 3. Petroleum wastewater if not handled properly may leak, leach or spill to pollute ground/surface water bodies. The common compounds present in petroleum wastewater are benzene, toluene, ethyl benzene, and xylenes (BTEX). BTEX having concentration of 100 µg/L was biodegraded using *Parachlorella kessleri* by Takáčová *et al.* [39] and found efficient results in 48 hours.

2.2 Microalgae in the Treatment of Heavy Metals (HMs) and Emerging Contaminants (ECs)

ECs are generally found in the wastewater effluent coming from landfills and pharmaceutical industries. The commonly found ECs are pharmaceuticals, personal care products (PCPs), endocrine disrupting compounds (EDCs) and pesticides. Microalgae have the potency to remove the ECs in the concentration range of 9-24 µg/L [15,26]. The removal of ECs using different genera of microalgae are shown in Table 4.

The untreated HMs disposal may cause adverse effects, because of the ineptitude in biodegradation causing bioaccumulation. This may further lead to biomagnification causing detrimental impacts on human health and environment. Microalgae can remove HMs by the mechanism of bio absorption and cell incorporation. Microalgae can sequester HMs and can become feasible method for bioremediating HMs in future [1,55]. The microalgae can remove HMs effectively [56] as compared to other conventional technologies if the concentration of HMs is in traces. *Chlamydomonas reinhardtii* can efficiently remove Cd (0.64-292 mg/g of dry biomass) and Hg^{2+} removal capacity of 107 mg/g [57]. The effectiveness of different species of microalgae in the removal of various heavy metals are shown in Table 5.

3. Photobioreactors (PBRs) used in the Bioremediation of Wastewater

PBRs are broadly classified as open and closed systems having their respective advantages and disadvantages. Open systems include open ponds, raceway ponds, scrubbers and tanks while closed systems include tubular PBR (bubble and airlift mechanism) and flat plate PBR [9]. Applicability of microalgae for wastewater treatment requires additional technological optimisation in the PBRs. The systems using microalgae for the treatment of wastewater can be categorised into: (i) Suspended microalgae systems, (ii) Immobilized microalgae systems [65].

3.1 Suspended Microalgae Systems for Wastewater Treatment

Pond systems are commonly used reactor systems for microalgae cultivation and wastewater treatment due to their low cost and simplicity of construction [66]. However, they have the drawbacks such as limited light supply, temperature variations, poor mixing, and low productivity of microalgal biomass. As the supply of CO_2 is not uniform and steady because of C:N:P imbalance and thus reducing the productivity of microalgal biomass [67]. However, high-rate algal ponds (HRAPs) can prove helpful to overcome some of these limitations by providing better mixing as they have paddle wheel stirrers and adequate gas intrusion. Improvised aeration and CO_2 supply can increase the biomass productivity and the removal rates of various contaminants [68]. The removal of N and P by microalgae suspended systems is usually in the range of 10-97% de-

Table 5. Effectiveness of Microalgae in the removal of Heavy Metals (HMs).

Species of Microalgae	Heavy metals	Removal%	Ref.
Scenedesmus sp.	Cadmium	73	[58]
Chlorella vulgaris	Chromium	50.7-80.3	[59]
Scenedesmus obliquus	Copper	72.4-91.7	[60]
Chlorella sp.	Lead	66.3	[61]
Psuedochlorococcum typicum	Mercury	97	[62]
Chlorella miniate	Nickel	60-73	[63]
Synechocystis sp.	Zinc	40	[63]
Synechocystis salina	Iron	66	[64]

pending upon the type of microalgae, culture mode, wastewater characterization, tank size and process parameters [69]. Some of the photobioreactor systems used for the co-cultivation of microalgae with different wastewaters are shown in Figure 5.

Closed systems provide better opportunities in terms of efficient light distribution and mixing (bubble or airlift systems) thereby increasing the biomass productivity and removal efficiency as compared to open pond system [72]. The removal of various ECs were evaluated by Matamoros *et al.* [73] by a pilot scale HRAP fed with an organic loading rate of 7-29 g COD/m^3/d and the results were represented as (i) Class-A having removal >90% (caffeine, ibuprofen); (ii) Class-B having removal 60-90% (naproxen, bisphenol A, tributyl phosphate); (iii) Class-C having removal 40-60% (diclofenac, benzotriazole); and (iv) Class-D having removal <30% (methyl paraben, 2,4-D).

3.2 Immobilized Microalgae Systems for Wastewater Treatment

Microalgae act as filters for wastewater containing N and P, HMs, and ECs. As the concentration of biomass is sometimes very low so the harvesting and downstream processing becomes costly. In this context, immobilization of microalgal cells has been proposed for circumventing the harvest problem as well as retaining the high-value algal biomass for further processing [74].

3.2.1 Microalgae Turf Scrubber

It utilizes the community of microalgae, cyanobacteria, and other microbes in the form of periphyton to treat municipal and agricultural wastewater. The mechanism is such that a substrate liner is provided for periphyton on the raceway having a mild slope. After that the wastewater is streamed through the growing biomass and the pollutants are degraded or filtered.

3.2.2 Fixed bed systems

They are based on stationary metrics (porous matrix or fibers) for microalgal immobilization. The factors which are crucial in the growth, stable formation and adhesion strength of the biofilm are high surface to volume ratios, hydrophobicity and surface material of the matrix used will govern the removal of pollutants present in the stream of wastewater. Sukačová *et al.* [75] demonstrated removal rates of about 92% using microalgae and cyanobacteria in a horizontal flat panel PBR.

3.2.3 Fluidized bed systems

Microalgal biomass is immobilized on a floating substratum which enhances the surface to volume ratios to a higher degree and promotes better light distribution by increasing the mixing capacity. They generally use carrageen beads, chitosan, or alginate to hold the microalgal biomass. The cells permeate the porous matrix of the beads and grow inside it.

Fluidized bed systems can be integrated with other PBRs (bubble column and stirred tank reactors) to obtain synergistic benefits in terms of growth and treatment. The growth and removal rate cannot be compared with fixed bed systems, as it depends upon the type

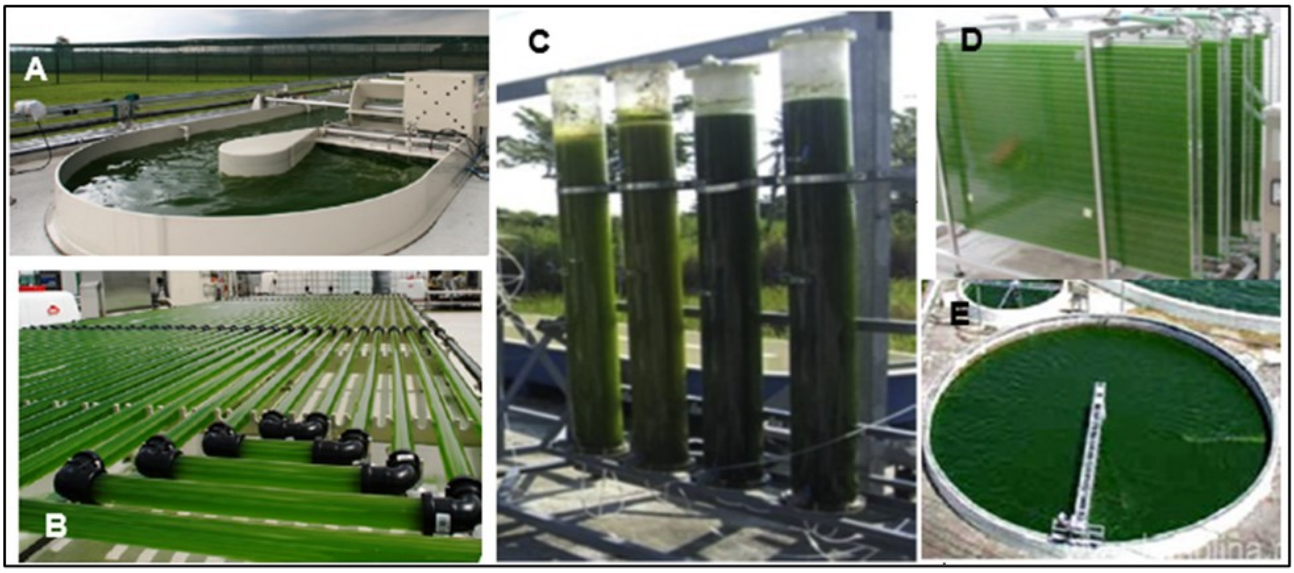


Figure 5. Open and closed PBR systems for microalgal coupled cultivation with wastewaters [70,71]

and material of immobilization matrix, type of microalgae and the characteristics of wastewater. Studies revealed the removal rate from 82-100% of pollutants from wastewater using fixed bed systems and carrageen-immobilized cells of *Chlorella vulgaris* [76].

During last couple of years various companies from Australia, US, and UK are working with a committed approach to produce algal biomass through different wastewater sources. The RNEW technology by Microbio-Engineering (US) used CO_2 aerated and mechanically agitated raceway ponds for the treatment of municipal wastewater containing high concentration of N and P, simultaneously producing algal biomass which is further utilized to produce biofuels [77]. Oswald technologies (U.S) have developed (AIWPS) based on the symbiotic consortium of bacteria and algae which is used in the removal of inorganic and organic pollutants contained in agricultural, municipal and industrial wastewater [78]. Algae systems (U.S) implemented a cost effective offshore PBR (floating system) working on environmental CO_2 and natural light and take up the nutrients/pollutants coming from the original source. The efficiency was quite high as it treated about 50,000 gallons/day of municipal wastewater while the algal biomass produced goes through hydrothermal liquefaction (HTL) carried onshore to obtain biofuels and biofertilizers [79].

The other option is to go for immobilized microalgae photobioreactor systems. One Water has developed the Algae Wheel system, an advanced algal-fixed film technology (Figure 6-D). The biofilm ecosystem attached to the Algae Wheels contains a diverse group of bacteria and algae, and their combined synergetic effect enhances the removal efficiency of the system.

The microalgae take up sunlight to fix CO_2, released by the bacteria. The polysaccharides, produced in photosynthesis, becomes the source of nutrients for bacteria. In turn, the bacteria can consume photosynthetically produced oxygen, resulting in self-regulating, stable, and ecological sustainable WWT system [80]. The revolving algal biofilm (RAB) system of Gross-Wen Technologies is made of an algae biofilm attached to vertically oriented rotating conveyor belts (Figure 6-E). While performing photoautotrophic growth at the gaseous phase, the attached microalgae fix N and P from the nutrient-rich liquid. The algal biomass of the RAB system can be easily scrapped from the surface of the RAB system avoiding expensive harvesting operations. The RAB system increased the productivity of algal biomass and efficiently removed the pollutants sulphate = 46%, TP = 80% and TN = 87% [81].

Some of the companies using microalgae in the treatment of wastewater and biomass production for various useful products are mentioned in Table 6, also incorporating the inno-

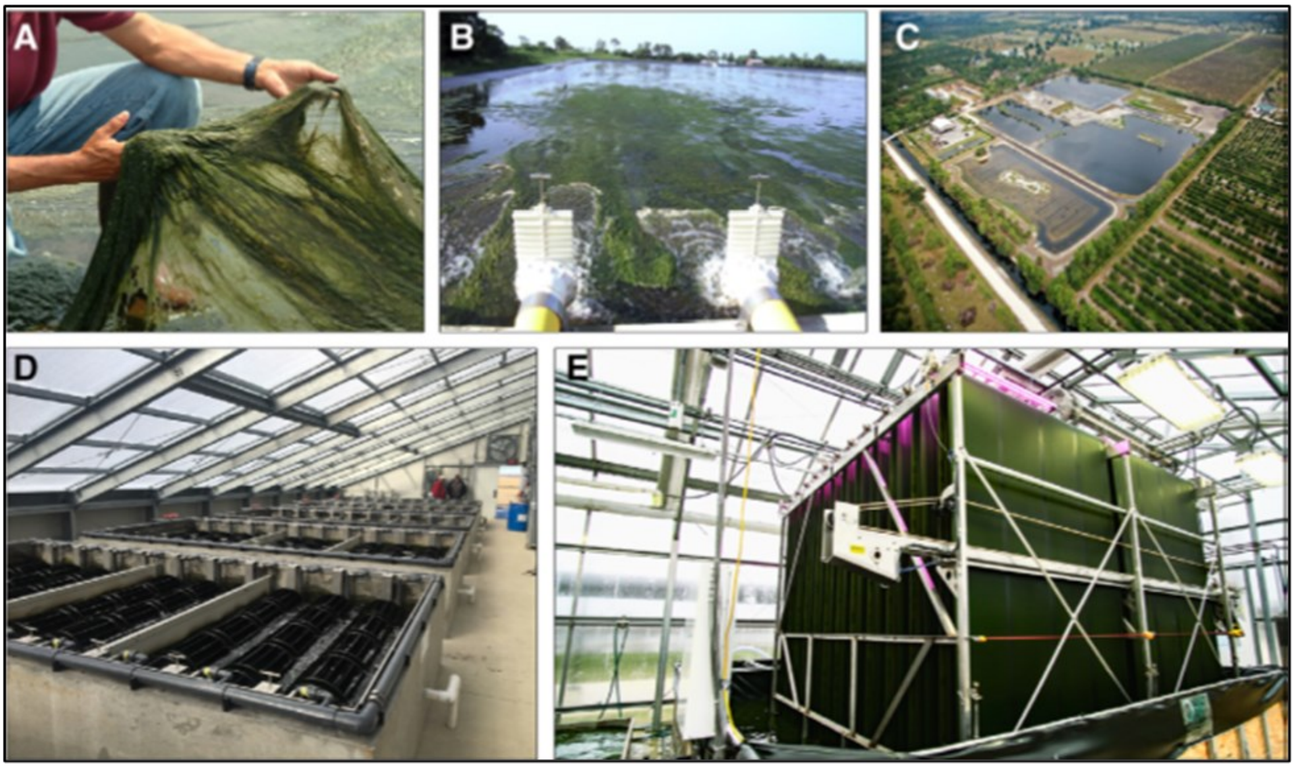


Figure 6. Immobilized systems for microalgae cultivation and wastewater treatment [65].

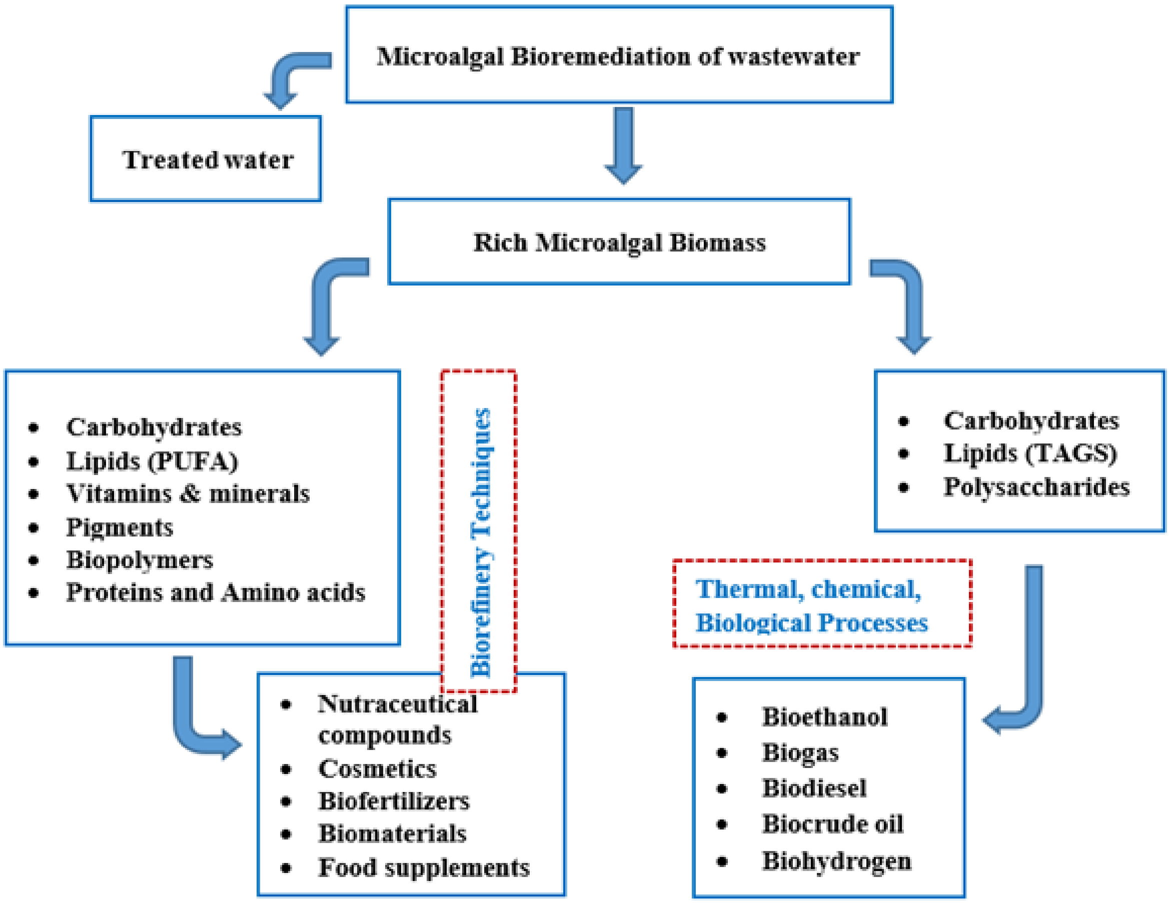


Figure 7. End use applications of microalgae cultivated in wastewater.

Table 6. Companies involved in the bioremediation of wastewaters using microalgae.

Technologies/Companies using microalgae for wastewater treatment	Mechanism/PBR	Pollutants/Wastewater	Utilization of Biomass produced	Ref
RNEW® Technology (Microbio-Engineering) U.S	Mechanically mixed, CO_2 gassed raceway ponds	N and P rich municipal wastewater	Biofuels	[82]
Advanced Integrated Wastewater Pond System (AIWPSR) or *Energy Ponds™* (Oswald green technologies) U.S	Employing bacterial algal consortium	Organic/inorganic pollutants from agricultural and industrial wastewaters	Biofertilizer Bioplastics Animal feed	[78]
Algae systems U.S	Offshore floating PBR using natural light and CO_2 conditions	50,000 Gallons/d Municipal wastewaters (75% TN, 93%TP and 93% BOD)	Biofuels biofertilizers	[79]
Algae Enterprises Australia	Closed PBR system	Municipal, agricultural, and industrial	Methane-Electricity	[83]
Algal Turf Scrubber (ATS) by *Hydro Mentia*	Immobilized System	Aquaculture wastewater, River water treatment	Biofertilizer, Biofuels	[84]
Algae Wheel® system by *One Water*	Immobilized system	Different sources of wastewater	Biofuels	[80]
RAB system of Gross-Wen Technologies	Immobilized System	Sulphate contained mining wastewater	Bioplastics	[85]

vative technologies used for the treatment. The microalgae species used by them are not known due to various ethical issues.

4. Downstream Applications (End Use) of Microalgae Cultivated in Wastewaters

Microalgae is having bright future in terms of wastewater bioremediation but still it is a daunting task to overcome the CAPEX and OPEX of the bulk scale cultivation and harvesting of microalgal biomass. Phycologists advocate that to prevail over this limitation wastewater treatment should be coupled with efficient downstream processing of microalgal biomass to obtain biofuels and other value-added derivatives [86]. End use applications of microalgae cultivated in wastewaters is shown in Figure 7.

Mostly microalgae are supposed to contain 20 to 50% lipids on a dry weight basis which are mainly C16-C18 fatty acids having the ability to be converted to high quality biodiesel using the process of transesterification [87]. *Nephroselmis sp.* was cultivated in the diluted industrial wastewater, leading to high lipid productivity and growth rate as compared to BBM (synthetic medium). It also contained greater concentrations of palmitic and oleic acids which are also helpful to produce biodiesel [88]. Carbohydrate is another major ingredient contained in microalgal biomass which can be exploited for bioethanol production. Microalgae have high concentrations of starch and cellulose which can be easily fermented.

The absence of lignin with low concentration of hemicellulose also favors the production of bioethanol. *Nannochloropsis oculata* and *Tetraselmis suecica* were cultivated in municipal wastewater and biomass produced was fermented using *Saccharomyces cerevisiae* and 4% bioethanol yield was achieved [89]. These were the end use applications when a fraction of microalgal biomass was utilized, on the other hand anaerobic digestion valorises whole of the biomass to produce biogas [90]. Anaerobic digestion using microalgal biomass is a recommended process because of the rigid cell wall possessed by microalgae. It was reported that during the batch mode of cultivation of *C. vulgaris, S. obliquus*, and *C. reinhardtii* consortium, the produced biomass can generate methane yield of 146 mL/g COD, during the anaerobic digestion [91].

Furthermore, *S. obliquus* was cultivated in municipal wastewater producing carbohydrate rich biomass which was later fermented using *Enterobacter aerogenes* producing biohydrogen yield of 56.8 mL/g VS [92]. It was reported that when *Chlorella* strain (PY-ZU1) was cultivated in s wine digestate, the biomass produced was considered suitable for food/feed as it contained 46% of proteins with fewer contaminants [93]. The biomass obtained from microalgal cultivation is also rich source of pigments (chlorophyl and carotenoids) which are useful for health benefits as they are antidiabetic, anti-inflammatory and antioxidant agents and work against cardiovascular diseases and cancer [94]. Study revealed that when *Phormidium autumnale* was cultivated with slaughterhouse wastewater heterotrophically to achieve carotenoid production of 108 tonnes per year [95]. As the microalgal biomass contains many more rich ingredients like PUFA, vitamins, phenols, poly-sterols which can further be processed to obtain biofertilizers, cosmetics and biomaterials, *etc.* [96].

5. Author's Perception in a Nutshell

The microalgae-based wastewater bioremediation [97] has various advantages: pollution control, especially, wastewater bioremediation, nutrients recovery, water restoration, CO_2 fixation, and biomass production. The performance of bioremediation and pollution control can be quantitatively evaluated by the following parameters, i.e.: (i) wastewater treatment {the removal of wastewater pollutants (total phosphorus (TP), COD, heavy metal, total nitrogen (TN), *etc.*)}; (ii) safeguarding climate: mitigation of greenhouse gases (the fixation of CO_2); (iii) reusability of culturing medium; (iv) Rich biomass is produced when microalgae is cultivated in wastewaters, which can be utilized as feed for aquaculture and biofertilizers in agriculture; and (v) chemical treatment produces toxic sludge while mechanical treatments are costly both can be avoided by using microalgal bioremediation; (vi) Bioremediation reduces the nutrient load, excess sludge formation while increases the dissolved oxygen levels by photosynthesis [98]. Species, like *Ankistrodesmus, Chlorella, Oscillatoria* and *Scenedesmus*, are proved to be able to treat paper and mill industrial wastewaters, dying, olive oil, through biosorption and biodegradation by the specifically extracellular ultrastructure of microalgae or micronutrient transporters, detoxifying in unique cellular compartments [99]. Still there are some challenges in coupling bioremediation of wastewater using microalgae such as selection and isolation of most suitable microalgal strain tolerant to the wastewater (fresh water or saline water algal strain) [100];

selection of wastewater which will become the growing habitat for that particular strain (nutrients balance) [101]; optimum pre-treatment methods for wastewater [102]; and risk of contamination, which is resolved by using closed photobioreactors [103]. The bioremediation is a sustainable solution for the treatment of wastewaters with a compelling potential for energy and nutrient recovery.

6. Conclusions

Bioremediation of wastewater using microalgae represent a wider area of future research and development. Microalgae is having great potential in terms of removal of pollutants such as COD, N, P, HMs, and ECs. Furthermore, the high values of N and P in different wastewaters make it possible to use them as nutrient source to produce microalgal biomass which can be valorized for biofuels and other value-added products. Nevertheless, microalgae can save fresh water and land as it can be cultivated in wastewater and PBR/ponds thus leading to sustainable environment. The effectiveness of fixed and fluidized bed systems with their mechanism is elaborated. There are indeed some bottlenecks like nutrient imbalance, lower productivity, and high cost of harvesting but they can be tackled by going forward in optimizing the process parameters and exploring more about the green expedient (microalgae).

Acknowledgement

The study was supported by the Algae research center, Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia.

Conflict of Interest

The authors have stated no conflict of interest.

References

[1] Abdel-Raouf, N., Al-Homaidan, A., Ibraheem, I. (2012). Microalgae and wastewater treatment. *Saudi Journal of Biological Sciences*, 19(3), 257–275. DOI: 10.1016/j.sjbs.2012.04.005

[2] Sousa, J.C., Ribeiro, A.R., Barbosa, M.O., Pereira, M.F.R, Silva, A.M. (2018). A review on environmental monitoring of water organic pollutants identified by EU guidelines. *Journal of Hazardous Materials*, 344, 146-162. DOI: 10.1016/j.jhazmat.2017.09.058

[3] Li, K., Liu, Q., Fang, F., Luo, R., Lu, Q., Zhou, W., Huo, S., Cheng, P., Liu, J., Addy, M. (2019). Microalgae-based wastewater treatment for nutrients recovery: A review. *Bioresource Technology*, 291, 121934. DOI: 10.1016/j.biortech.2019.121934

[4] Chowdhury, S., Mazumder, M.J., Al-Attas, O., Husain, T. (2016). Heavy metals in drinking water: occurrences, implications, and future needs in developing countries. *Science of the total Environment*, 569, 476-488. DOI: 10.1016/j.scitotenv.2016.06.166

[5] Eerkes-Medrano, D., Leslie, H.A., Quinn, B. (2019). Microplastics in drinking water: A review and assessment. *Current Opinion in Environmental Science & Health*, 7, 69-75. DOI: 10.1016/j.coesh.2018.12.001

[6] Farmer, A. (2018). Phosphate pollution: a global overview of the problem. Phosphorus: Polluter and Resource of The Future—Removal and Recovery From Wastewater; Schaum, C., Ed, p. 35-55. DOI: 10.2166/9781780408361_035

[7] Yousuf, A. (2020). Fundamentals of Microalgae Cultivation, in *Microalgae Cultivation for Biofuels Production*. Elsevier, p. 1-9. DOI: 10.1016/B978-0-12-817536-1.00001-1

[8] Okoro, V., Azimov, U., Munoz, J., Hernandez, H.H., Phan, A.N. (2019). Microalgae cultivation and harvesting: Growth performance and use of flocculants-A review. *Renewable and Sustainable Energy Reviews*, 115, 109364. DOI: 10.1016/j.rser.2019.109364

[9] Yin, Z., Zhu, L., Li, S., Hu, T., Chu, R., Mo, F., Hu, D., Liu, C., Li, B. (2020). A comprehensive review on cultivation and harvesting of microalgae for biodiesel production: Environmental pollution control and future directions. *Bioresource Technology*, 301, 122804. DOI: 10.1016/j.biortech.2020.122804

[10] Gupta, S., Pawar, S.B., Pandey, R. (2019). Current practices and challenges in using microalgae for treatment of nutrient rich wastewater from agro-based industries. *Science of the Total Environment*, 687, 1107-1126. DOI: 10.1016/j.scitotenv.2019.06.115

[11] Borowitzka, M.A., Borowitzka, L.J. (1988). *Micro-algal Biotechnology*. Cambridge University Press.

[12] Varshney, P., Mikulic, P., Vonshak, A., Beardall, J., Wangikar, P.P. (2015). Extremophilic micro-algae and their potential contribution in biotechnology. *Bioresource Technology*, 184, 363-372. DOI: 10.1016/j.biortech.2014.11.040

[13] Schmidt, R.A., Wiebe, M.G., Eriksen, N.T. (2005). Heterotrophic high cell-density fed-batch cultures of the phycocyanin-producing red alga Galdieria sulphuraria. *Biotechnology and Bioengineering*, 90(1), 77-84. DOI: 10.1002/bit.20417

[14] Wan, M., Wang, Z., Zhang, Z., Wang, J., Li, S., Yu, A., Li, Y. (2016). A novel paradigm for the high-efficient production of phycocyanin from Galdieria sulphuraria. *Bioresource Technology*, 218, 272-278. DOI: 10.1016/j.biortech.2016.06.045

[15] Sakarika, M., Koutra, E., Tsafrakidou, P., Terpou, A., Kornaros, M. (2020). *Microalgae-based Remediation of Wastewaters*. in Microalgae Cultivation for Biofuels Production, Elsevier. p. 317-335. DOI: 10.1016/B978-0-12-817536-1.00020-5

[16] Lim, S.-L., Chu, W.-L., Phang, S.-M. (2010). Use of Chlorella vulgaris for bioremediation of textile wastewater. Bioresource *Technology*, 101(19), 7314-7322. DOI: 10.1016/j.biortech.2010.04.092

[17] Riaño, B., Molinuevo, B., García-González, M. (2011). Treatment of fish processing wastewater with microalgae-containing microbiota. *Bioresource Technology*, 102(23), 10829-10833. DOI: 10.1016/j.biortech.2011.09.022

[18] Kshirsagar, A.D. (2013). Bioremediation of wastewater by using microalgae: an experimental study. *International Journal of Life Science Biotechnology and Pharma Research*, 2(3), 339-346.

[19] Sahu, O. (2014). Reduction of organic and inorganic pollutant from waste water by algae. *International Letters of Natural Sciences*, 13, 1-8.

[20] Ji, M.-K., Abou-Shanab, R.A., Hwang, J.-H. Timmes, T.C., Kim, H.-C., Oh, Y.-K., Jeon, B.-H. (2013). Removal of nitrogen and phosphorus from piggery wastewater effluent using the green microalga Scenedesmus obliquus. *Journal of Environmental Engineering*, 139(9), 1198-1205. DOI: 10.1061/(ASCE)EE.1943-7870.0000726

[21] Ahmad, F., Khan, A., Yasar, A. (2013). Comparative phycoremediation of sewage water by various species of algae. *Proceedings of the Pakistan Academy of Sciences*, 50(2), 131-139.

[22] Órpez, R., Martínez, M.E., Hodaifa, G., El Yousfi, F., Jbari, N., Sánchez, S. (2009). Growth of the microalga Botryococcus braunii in secondarily treated sewage. *Desalination*, 246(1-3), 625-630. DOI: 10.1016/j.desal.2008.07.016

[23] Dominic, V., Murali, S., Nisha, M. (2009). Phycoremediation efficiency of three micro algae chlo-rella vulgaris, synechocystis salina and gloeocapsa gelatinosa. *SB Academic Review*, 16(1), 138-146.

[24] Van Den Hende, S., Carré, E., Cocaud, E., Beelen, V., Boon, N., Vervaeren, H. (2014). Treatment of industrial wastewaters by microalgal bacterial flocs in sequencing batch reactors. *Bioresource Technology*, 161, 245-254. DOI: 10.1016/j.biortech.2014.03.057

[25] Gani, P., Sunar, N.M., Matias-Peralta, H.M., Abdul Latiff, A.A., Kamaludin, N.S., Parjo, U.K., Emparan, Q., Er. C.M. (2015). Experimental study for phycoremediation of Botryococcus sp. on greywater. In *Applied Mechanics and Materials*. Trans Tech Publ. DOI: 10.4028/www.scientific.net/AMM.773-774.1312

[26] Ahmed, M.B., Zhou, J.L., Ngo, H.H., Guo, W., Thomaidis, N.S., Xu, J. (2017). Progress in the biological and chemical treatment technologies for emerging contaminant removal from wastewater: a critical review. *Journal of Hazardous Materials*, 323, 274-298. DOI: 10.1016/j.jhazmat.2016.04.045

[27] Zheng, H., Liu, M., Lu, Q., Wu, X., Ma, Y., Cheng, Y., Addy, M., Liu, Y., Ruan, R. (2018). Balancing carbon/nitrogen ratio to improve nutrients removal and algal biomass production in piggery and brewery wastewaters. *Bioresource Technology*, 249, 479-486. DOI: 10.1016/j.biortech.2017.10.057

[28] Ahmad, I., Abdullah, N., Yuzir, A., Koji, I., Mohamad. S.E. (2020). Efficacy of microalgae as a nutraceutical and sustainable food supplement. In *3rd ICA Research Symposium (ICARS) 2020*. Johor, Malaysia.

[29] Egberomoh, G., Fagade, O. (2016). Microalgal-bacterial consortium in polyaromatic hydrocarbon degradation of petroleum-based effluent. *Journal of Bioremediation and Biodegradation*, 7(4), 359. DOI: 10.4172/2155-6199.1000359

[30] Choi, Y.-K., Jang, H.M., Kan, E. (2018). Microalgal biomass and lipid production on dairy effluent using a novel microalga, Chlorella sp. isolated from dairy wastewater. *Biotechnology and Bioprocess Engineering*, 23(3), 333-340. DOI: 10.1007/s12257-018-0094-y

[31] Kim, S., Park, J.-e., Cho, Y.-B., Hwang, S.-J. (2013). Growth rate, organic carbon and nutrient removal rates of Chlorella sorokiniana in autotrophic, heterotrophic and mixotrophic conditions. *Bioresource Technology*, 144, 8-13. DOI: 10.1016/j.biortech.2013.06.068

[32] Zhang, Q., Li, X., Guo, D., Ye, T., Xiong, M., Zhu, L., Liu, C., Jin, S., Hu, Z. (2018). Operation of a vertical algal biofilm enhanced raceway pond for nutrient removal and microalgae-based byproducts production under different wastewater loadings. *Bioresource Technology*, 253, 323-332. DOI: 10.1016/j.biortech.2018.01.014

[33] Zhou, W., Li, Y., Gao, Y., Zhao, H. (2017). Nutrients removal and recovery from saline wastewater by Spirulina platensis. *Bioresource Technology*, 245, 10-17. DOI: 10.1016/j.biortech.2017.08.160

[34] Wang, J.-H., Zhang, T.-Y., Dao, G.-H., Xu, X.-Q., Wang, X.-X., Hu, H.-Y. (2017). Microalgae-based advanced municipal wastewater treatment for reuse in water bodies. *Applied microbiology and biotechnology*, 101(7), 2659-2675. DOI: 10.1007/s00253-017-8184-x

[35] Shi, J., Podola, B., Melkonian, M. (2014). Application of a prototype-scale Twin-Layer photobioreactor for effective N and P removal from different process stages of municipal wastewater by immobilized microalgae. *Bioresource Technology*, 154, 260-266. DOI: 10.1016/j.biortech.2013.11.100

[36] Hadiyanto, H., Christwardhana, M., Soetrisnanto, D. (2013). Phytoremediations of palm oil mill effluent (POME) by using aquatic plants and microalgae for biomass production. *Journal of Environmental Science and Technology*, 6(2), 79-90. DOI: 10.3923/jest.2013.79.90

[37] Hodaifa, G., Romero, A.M., Halioui, M., Sánchez, S. (2017). Combined Process for Olive Oil Mill Wastewater Treatment Based in Flocculation, Photolysis, Microfiltration and Microalgae Culture. in *Euro-Mediterranean Conference for Environmental Integration*. Springer. DOI: 10.1007/978-3-319-70548-4_326

[38] Ghazal, F.M., Mahdy, E.-S.M., EL-Fattah, M.S.A., EL-Sadany, A.E.G.Y., Doha, N.M.E. (2018). The use of microalgae in bioremediation of the textile wastewater effluent. *Nature and Science*, 16, 98-104.

[39] Takáčová, A., Smolinská, M., Semerád, M., Matúš, P. (2015). Degradation of btex by microalgae Parachlorella kessleri. *Petroleum & Coal*, 57(2), 101-107.

[40] Lv, J., Feng, J., Liu, Q., Xie, S. (2017). Microalgal cultivation in secondary effluent: recent developments and future work. *International Journal of Molecular Sciences*, 18(1), 79. DOI: 10.3390/ijms18010079

[41] Choi, H.-J. (2016). Dairy wastewater treatment using microalgae for potential biodiesel application. *Environmental Engineering Research*, 21(4), 393-400. DOI: 10.4491/eer.2015.151

[42] Michels, M.H., Vaskoska, M., Vermuë, M.H., Wijffels, R.H. (2014). Growth of Tetraselmis suecica in a tubular photobioreactor on wastewater from a fish farm. *Water Research*, 65, 290-296. DOI: 10.1016/j.watres.2014.07.017

[43] Sforza, E., Al Emara, M.K., Sharif, A., Bertucco, A. (2015). Exploitation of urban landfill leachate as nutrient source for microalgal biomass production. *Chemical Engineering Transactions*, 43, 373-378. DOI: 10.3303/CET1543063

[44] You, S., Ok, Y.S., Chen, S.S., Tsang, D.C., Kwon, E.E, Lee, J., Wang, C.-H. (2017). A critical review on sustainable biochar system through gasification: energy and environmental applications. *Bioresource Technology*, 246, 242-253. DOI: 10.1016/j.biortech.2017.06.177

[45] Ding, T., Lin, K., Yang, B., Yang, M., Li, J., Li, W., Gan, J. (2017). Biodegradation of naproxen by freshwater algae Cymbella sp. and Scenedesmus quadricauda and the comparative toxicity. *Bioresource Technology*, 238, 164-173. DOI: 10.1016/j.biortech.2017.04.018

[46] Escapa, C., Coimbra, R., Paniagua, S., García, A., Otero, M. (2016). Comparative assessment of diclofenac removal from water by different microalgae strains. *Algal Research*, 18, 127-134. DOI: 10.1016/j.algal.2016.06.008

[47] Wang, T., Yang, W.-L., Hong, Y., Hou, Y.-L. (2016). Magnetic nanoparticles grafted with amino-riched dendrimer as magnetic flocculant for efficient harvesting of oleaginous microalgae. *Chemical Engineering Journal*, 297, 304-314. DOI: 10.1016/j.cej.2016.03.038

[48] Escapa, C., Coimbra, R., Paniagua, S., García, A., Otero, M. (2015). Nutrients and pharmaceuticals removal from wastewater by culture and harvesting of Chlorella sorokiniana. *Bioresource Technology*, 185, 276-284. DOI: 10.1016/j.biortech.2015.03.004

[49] Cheng, J., Ye, Q., Li, K., Liu, J., Zhou, J. (2018). Removing ethinylestradiol from wastewater by microalgae mutant Chlorella PY-ZU1 with CO_2 fixation. *Bioresource Technology*, 249, 284-289. DOI: 10.1016/j.biortech.2017.10.036

[50] Gattullo, C.E., Bährs, H., Steinberg, C.E., Loffredo, E. (2012). Removal of bisphenol A by the freshwater green alga Monoraphidium braunii and the role of natural organic matter. *Science of the Total Environment*, 416, 501-506. DOI: 10.1016/j.scitotenv.2011.11.033

[51] Xiong, J.-Q., Kurade, M.B., Jeon, B.-H. (2017). Biodegradation of levofloxacin by an acclimated freshwater microalga, Chlorella vulgaris. *Chemical Engineering Journal*, 313, 1251-1257. DOI: 10.1016/j.cej.2016.11.017

[52] Kurade, M.B., Kim, J.R., Govindwar, S.P., Jeon, B.-H. (2016). Insights into microalgae mediated biodegradation of diazinon by Chlorella vulgaris: microalgal tolerance to xenobiotic pollutants and metabolism. *Algal Research*, 20, 126-134. DOI: 10.1016/j.algal.2016.10.003

[53] Wang, S., Poon, K., Cai, Z. (2018). Removal and metabolism of triclosan by three different microalgal species in aquatic environment. *Journal of Hazardous Materials*, 342, 643-650. DOI: 10.1016/j.jhazmat.2017.09.004

[54] Liu, W., Chen, Q., He, N., Sun, K., Sun, D., Wu, X., Duan, S. (2018). Removal and Biodegradation of 17β-Estradiol and Diethylstilbestrol by the freshwater microalgae Raphidocelis subcapitata. *International Journal of Environmental Research and Public Health*, 15(3), 452. DOI: 10.3390/ijerph15030452

[55] Perales-Vela, H.V., Peña-Castro, J.M., Canizares-Villanueva, R.O. (2006). Heavy metal detoxification in eukaryotic microalgae. *Chemosphere*, 64(1), 1-10. DOI: 10.1016/j.chemosphere.2005.11.024

[56] Al-Jabri, H., Das, P., Khan, S., Thaher, M., Abdul Quadir, M. (2021). Treatment of Wastewaters by Microalgae and the Potential Applications of the Produced Biomass—A Review. *Water*, 13(1), 27. DOI: 10.3390/w13010027

[57] Kumar, K.S., Dahms, H.-U., Won, E.-J, Lee, J.-S., Shin, K.-H. (2015). Microalgae–A promising tool for heavy metal remediation. *Ecotoxicology and Environmental Safety*, 113, 329-352. DOI: 10.1016/j.ecoenv.2014.12.019

[58] Travieso, L., Canizares, R., Borja, R., Benitez, F., Dominguez, A., Valiente, V. (1999). Heavy metal removal by microalgae. *Bulletin of Environmental Contamination and Toxicology*, 62(2), 144-151.

[59] Sibi, G. (2016). Biosorption of chromium from electroplating and galvanizing industrial effluents under extreme conditions using Chlorella vulgaris. *Green Energy & Environment*, 1(2), 172-177. DOI: 10.1016/j.gee.2016.08.002

[60] Li, Y., Yang, X., Geng, B. (2018). Preparation of immobilized sulfate-reducing bacteria-microalgae beads for effective bioremediation of copper-containing wastewater. *Water, Air, & Soil Pollution*, 229(3), 1-13. DOI: 10.1007/s11270-018-3709-1

[61] Kumar, R., Goyal, D. (2012). Waste water treatment and metal (Pb 2+, Zn 2+) removal by microalgal based stabilization pond system. *Indian Journal of Microbiology*, 50(1), 34-40. DOI: 10.1007/s12088-010-0063-4

[62] Shanab, S., Essa, A., Shalaby, E. (2012). Bioremoval capacity of three heavy metals by some microalgae species (Egyptian Isolates). *Plant Signaling & Behavior*, 7(3), 392-399. DOI: 10.4161/psb.19173

[63] Chong, A., Wong, Y., Tam, N. (2000). Performance of different microalgal species in removing nickel and zinc from industrial wastewater. *Chemosphere*, 41(1-2), 251-257. DOI: 10.1016/S0045-6535(99)00418-X

[64] Worku, A., Sahu, O. (2014). Reduction of heavy metal and hardness from ground water by algae. *Journal of Applied & Environmental Microbiology*, 2(3), 86-89. DOI: 10.12691/jaem-2-3-5

[65] Wollmann, F., Dietze, S., Ackermann, J.U., Bley, T., Walther, T., Steingroewer, J., Krujatz, F. (2019). Microalgae wastewater treatment: biological and technological approaches. *Engineering in Life Sciences*, 19(12), 860-871. DOI: 10.1002/elsc.201900071

[66] Barry, A., Wolfe, A., English, C., Ruddick, C., Lambert, D. (2016). National algal biofuels technology review. US Department of Energy, Office of Energy Efficiency and Renewable Energy, Bioenergy Technologies Office. DOI: 10.2172/1259407

[67] Park, J., Craggs, R., Shilton, A. (2011). Wastewater treatment high rate algal ponds for biofuel production. *Bioresource Technology*, 102(1), 35-42. DOI: 10.1016/j.biortech.2010.06.158

[68] Young, P., Taylor, M., Fallowfield, H. (2017). Mini-review: high rate algal ponds, flexible systems for sustainable wastewater treatment. *World Journal of Microbiology and Biotechnology*, 33(6), 117. DOI: 10.1007/s11274-017-2282-x

[69] El Hafiane, F., El Hamouri, B. (2005). Anaerobic reactor/high rate pond combined technology for sewage treatment in the Mediterranean area. *Water Science and Technology*, 51(12), 125-132. DOI: 10.2166/wst.2005.0445

[70] Kerestecioğlu, F.Ö., Pekmezci, Y.T. (2019). Defining the Problems of Integrated Algae Photobioreactor Systems to Architecture. *International Journal of Engineering Science and Application*, 3(2), 52-70.

[71] Chang, J.-S., Show, P.-L., Ling, T.-C., Chen, C.-Y., Ho, S.-H., Tan, C.-H., Nagarajan, D., Phong, W.-N. (2017). Photobioreactors, in Current developments in biotechnology and bioengineering. Elsevier. p. 313-352. DOI: 10.1016/B978-0-444-63663-8.00011-2

[72] Arbib, Z., Ruiz, J., Álvarez-Díaz, P., Garrido-Pérez, C., Barragan, J., Perales, J.A. (2013). Long term outdoor operation of a tubular airlift pilot photobioreactor and a high rate algal pond as tertiary treatment of urban wastewater. *Ecological Engineering*, 52, 143-153. DOI: 10.1016/j.ecoleng.2012.12.089

[73] Matamoros, V., Gutiérrez, R., Ferrer, I., García, J., Bayona, J.M. (2015). Capability of microalgae-based wastewater treatment systems to remove emerging organic contaminants: a pilot-scale study. *Journal of Hazardous Materials*, 288, 34-42. DOI: 10.1016/j.jhazmat.2015.02.002

[74] Mallick, N. (2020). Immobilization of Microalgae, in Immobilization of Enzymes and Cells. Springer. p. 453-471. DOI: 10.1007/978-1-0716-0215-7_31

[75] Sukačová, K., Trtílek, M., Rataj, T. (2015). Phosphorus removal using a microalgal biofilm in a new biofilm photobioreactor for tertiary wastewater treatment. *Water Research*, 71, 55-63. DOI: 10.1016/j.watres.2014.12.049

[76] Lau, P., Tam, N., Wong, Y. (1998). Effect of carrageenan immobilization on the physiological activities of Chlorella vulgaris. *Bioresource Technology*, 63(2), 115-121. DOI: 10.1016/S0960-8524(97)00111-9

[77] Sing, S.F., Isdepsky, A., Borowitzka, M.A., Moheimani, N.R. (2013). Production of biofuels from microalgae. *Mitigation and Adaptation Strategies for Global Change*, 18(1), 47-72. DOI: 10.1007/s11027-011-9294-x

[78] Green, F.B., Lundquist, T., Oswald, W. (1995). Energetics of advanced integrated wastewater pond systems. *Water Science and Technology*, 31(12), 9-20. DOI: 10.1016/0273-1223(95)00488-9

[79] Green, F., Lundquist, T., Quinn, N., Zarate, M., Zubieta, I., Oswald, W. (2003). Selenium and nitrate removal from agricultural drainage using the AIWPS® technology. *Water Science and Technology*, 48(2), 299-305. DOI: 10.2166/wst.2003.0134

[80] Johnson, D.B., Schideman, L.C., Canam, T., Hudson, R.J. (2018). Pilot-scale demonstration of efficient ammonia removal from a high-strength municipal wastewater treatment sidestream by algal-bacterial biofilms affixed to rotating contactors. *Algal Research*, 34, 143-153. DOI: 10.1016/j.algal.2018.07.009

[81] Gross, M., Henry, W., Michael, C., Wen, Z. (2013). Development of a rotating algal biofilm growth system for attached microalgae growth with in situ biomass harvest. *Bioresource Technology*, 150, 195-201. DOI: 10.1016/j.biortech.2013.10.016

[82] Craggs, R.J., Lundquist, T.J., Benemann, J.R. (2013). Wastewater treatment and algal biofuel production, in Algae for biofuels and energy. Springer. p. 153-163. DOI: 10.1007/978-94-007-5479-9_9

[83] Montingelli, M., Tedesco, S., Olabi, A. (2015). Biogas production from algal biomass: A review. *Renewable and Sustainable Energy Reviews*, 43, 961-972. DOI: 10.1016/j.rser.2014.11.052

[84] Kangas, P., Mulbry, W., Klavon, P., Laughinghouse, H.D., Adey, W. (2007). High diversity within the periphyton community of an algal turf scrubber on the Susquehanna River. *Ecological Engineering*, 108, 564-572. DOI: 10.1016/j.ecoleng.2017.05.010

[85] Zhao, X., Kumar, K., Gross, M.A., Kunetz, T.E., Wen, Z. (2018). Evaluation of revolving algae biofilm reactors for nutrients and metals removal from sludge thickening supernatant in a municipal wastewater treatment facility. *Water Research*, 143, 467-478. DOI: 10.1016/j.watres.2018.07.001

[86] Borowitzka, M.A. (2013). High-value products from microalgae—their development and commercialisation. *Journal of applied phycology*, 25(3), 743-756. DOI: 10.1007/s10811-013-9983-9

[87] Chiu, S.-Y., Kao, C.-Y., Chen, T.-Y., Chang, Y.-B., Kuo, C.-M., Lin, C.-S. (2015). Cultivation of microalgal Chlorella for biomass and lipid production using wastewater as nutrient resource. *Bioresource Technology*, 184, 179-189. DOI: 10.1016/j.biortech.2014.11.080

[88] Ji, M.-K., Yun, H.-S., Hwang, B.S., Kabra, A.N., Jeon, B.-H., Choi, J. (2016). Mixotrophic cultivation of Nephroselmis sp. using industrial wastewater for enhanced microalgal biomass production. *Ecological Engineering*, 95, 527-533. DOI: 10.1016/j.ecoleng.2016.06.017

[89] Reyimu, Z., Özçimen, D. (2017). Batch cultivation of marine microalgae Nannochloropsis oculata and Tetraselmis suecica in treated municipal wastewater toward bioethanol production. *Journal of Cleaner Production*, 150, 40-46. DOI: 10.1016/j.jclepro.2017.02.189

[90] Ahmad, I., N. Abdullah, I. Koji, A. Yuzir, and S. Mohamad (2020) Anaerobic Digestion of Microalgae: Outcomes, Opportunities and Obstructions. Latin American Meetings on Anaerobic Digestion. p. 40-43

[91] Molinuevo-Salces, B., Mahdy, A., Ballesteros, M., González-Fernández, C. (2016). From piggery wastewater nutrients to biogas: microalgae biomass revalorization through anaerobic digestion. *Renewable Energy*, 96, 1103-1110. DOI: 10.1016/j.renene.2016.01.090

[92] Batista, A.P., Ambrosano, L., Graça, S., Sousa, C., Marques, P.A., Ribeiro, B., Botrel, E.P., Neto, P.C., Gouveia, L. (2015). Combining urban wastewater treatment with biohydrogen production–an integrated microalgae-based approach. *Bioresource Technology*, 184, 230-235. DOI: 10.1016/j.biortech.2014.10.064

[93] Cheng, J., Xu, J., Huang, Y., Li, Y., Zhou, J., Cen, K. (2015). Growth optimisation of microalga mutant at high CO_2 concentration to purify undiluted anaerobic digestion effluent of swine manure. *Bioresource Technology*, 177, 240-246. DOI: 10.1016/j.biortech.2014.11.099

[94] Gille, A., Neumann, U., Louis, S., Bischoff, S.C., Briviba, K. (2018). Microalgae as a potential source of carotenoids: Comparative results of an in vitro digestion method and a feeding experiment with C57BL/6J mice. *Journal of Functional Foods*, 49, 285-294. DOI: 10.1016/j.jff.2018.08.039

[95] Rodrigues, D.B., Flores, É.M., Barin, J.S., Mercadante, A.Z., Jacob-Lopes, E., Zepka, L.Q. (2014). Production of carotenoids from microalgae cultivated using agroindustrial wastes. *Food Research International*, 65, 144-148. DOI: 10.1016/j.foodres.2014.06.037

[96] Alobwede, E., Leake, J.R., Pandhal, J. (2019). Circular economy fertilization: Testing micro and macro algal species as soil improvers and nutrient sources for crop production in greenhouse and field conditions. *Geoderma*, 334, 113-123. DOI: 10.1016/j.geoderma.2018.07.049

[97] Gani, P., Mohamed Sunar, N., Matias Peralta, H.M., Abdul Latiff, A.A., Parjo, U.K. (2015). Phycoremediation of wastewaters and potential hydrocarbon from microalgae: a review. *Advances in Environmental Biology*, 9(20), 1-8.

[98] Ahmad, I., Yuzir, A., Mohamad, S., Iwamoto, K., Abdullah, N. (2021). Role of Microalgae in Sustainable Energy and Environment. *IOP Conference Series: Materials Science and Engineering*, 1051, 012059. DOI: 10.1088/1757-899X/1051/1/012059

[99] Singh, K., Arora, S. (2011). Removal of synthetic textile dyes from wastewaters: a critical review on present treatment technologies. *Critical Reviews in Environmental Science and Technology*, 41(9), 807-878. DOI: 10.1080/10643380903218376

[100] Wolf, J., Ross, I.L., Radzun, K.A., Jakob, G., Stephens, E., Hankamer, B. (2015). High-throughput screen for high performance microalgae strain selection and integrated media design. *Algal Research*, 11, 313-325. DOI: 10.1016/j.algal.2015.07.005

[101] Solovchenko, A., Verschoor, A.M., Jablonowski, N.D., Nedbal, L. (2016). Phosphorus from wastewater to crops: An alternative path involving microalgae. *Biotechnology Advances*, 34(5), 550-564. DOI: 10.1016/j.biotechadv.2016.01.002

[102] Montemezzani, V., Duggan, I.C., Hogg, I.D., Craggs, R.J. (2015). A review of potential methods for zooplankton control in wastewater treatment High Rate Algal Ponds and algal production raceways. *Algal Research*, 11, 211-226. DOI: 10.1016/j.algal.2015.06.024.

[103] Salama, E.-S., Kurade, M.B., Abou-Shanab, R.A., El-Dalatony, M.M., Yang, I.-S., Min, B., Jeon, B.-H. (2017). Recent progress in microalgal biomass production coupled with wastewater treatment for biofuel generation. *Renewable and Sustainable Energy Reviews*, 79, 1189-1211. DOI: 10.1016/j.rser.2017.05.091

Selected and Revised Papers from International Conference on Sustainable Energy and Catalysis 2021 (ICSEC 2021) (https://engineering.utm.my/chemicalenergy/icsec2021/) (School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 16-17th February 2021) after Peer-reviewed by Scientific Committee of ICSEC 2021 and Peer-Reviewers of Bulletin of Chemical Reaction Engineering & Catalysis.
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