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REVIEW

Phycoremediation of wastewater by microalgae: a review

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Abstract
Wastewater treatment requires the removal of contaminants, solids, nutrients, coliforms, and pathogenic bacteria. Classical treatments require high energy and induce secondary pollution by disinfectants. Alternatively, phycoremediation, which involves the use of algae to clean water, appears smarter and more sustainable because compounds such as nitrogen, phosphorus, sulfur, and minerals appear as 'nutrients' to feed algae rather than 'contaminants'. Phycoremediation thus allows to remove phosphates, nitrates, heavy metals, pesticides, hydrocarbons, nitrogen, and phosphorus. Moreover, the conditions favoring algal growth are disfavoring bacterial growth, which prevents the proliferation of pathogenic bacteria and improves water disinfection. Open pond systems have low maintenance, simple design, and reduce carbon footprint. Here we review factors controlling wastewater phycoremediation, and the most common systems. Microalgae are the main species used for phycoremediation. Efficiency is controlled by biotic factors, abiotic factors and algal strains. Photobioreactors appear unsuitable for large-scale applications due to cost, complicated operational procedures and scaling-up difficulties. Open pond systems are ideal for providing clean water in developing countries.

Keywords Microalgae · Wastewater phycoremediation systems · Wastewater treatment via algae

Abbreviations

AIWPS	Advanced integrated wastewater pond system
HRAP	High rate algal pond
HRAPs	High rate algal ponds
BOD_5	Biochemical oxygen demand for 5 days test

Introduction

Organic, inorganic and artificial elements are the main compounds of the wastewater. The majority of the organic carbon in sewage is made of proteins, carbohydrates, fats, amino acids, and volatile acids. The inorganic quantities comprised large amounts of ammonium, bicarbonate, calcium, chlorine, magnesium, phosphate, potassium, sodium, sulfur, and heavy metals (Lim et al. 2010). If the contaminants are transferred to living organisms, they may cause bioaccumulation and diseases (Akhil et al. 2021). Microalgae, freshwater as well as marine ones, are suitable for the treatment of wastewaters from numerous sources like agricultural, municipal, or industrial processes (Van Den Hende et al. 2014). The algae in the wastewater treatment process can remove phosphates and nitrates as well as heavy metals, pesticides, and hydrocarbons in a process called phycoremediation (Phang et al. 2015). This ability to utilize the nutrients from the wastewaters as well as nitrogen and phosphorus during their growth makes them prominent species for the bioremediation of wastewater bodies (Aslan and Kapdan 2006). Also, algae are known for their bactericidal abilities capable of reducing the proliferation of pathogenic bacteria (Dor 1980). Algal systems have traditionally been employed as a tertiary process in wastewater treatment. The tertiary treatment during wastewater treatment has a goal of the removal of all organic ions utilizing biological or chemical treatments (Abdel-Raouf et al. 2012). Biological treatment performs well compared to the chemical ones, as is cost-efficient and does not generate additional pollution, something that the chemical treatments do (Hammouda et al. 1995). The wastewater treatment industry focuses on the removal of biochemical oxygen demand, a measure of the quantity of oxygen required to remove waste organic matter from the water via the process of decomposition by aerobic bacteria (Orellana et al. 2011) of nutrients, solids, and toxic compounds. Five steps are utilized for wastewater

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treatment. The preliminary treatment that removes heavy solids hazardous for the treatment plant. The primary treatment removes solids by gravity. The secondary treatment focuses on the removal of the biochemical oxygen demand exerted by reducing organic matter. This is achieved by the use of mixed populations of heterotrophic bacteria that utilize the organic components for their growth. The tertiary treatment, and the disinfection of wastewater mostly via the use of chlorine, although the use of ozone (ozonation) or ultraviolet light is also under consideration in wastewater disinfection (Abdel-Raouf et al. 2012).

Researchers have focused on improving techniques for exploiting the fast-growing rates of the microalgae together with designing and developing wastewater treatment facilities to optimize wastewater treatment. Higher contents of inorganic carbonates, chlorides, nitrates, oxalates, and sulfates in algae provoke environmental challenges during the algae processing for biofuel application (Vassilev and Vassileva 2016). The biomass of the algae produced during the wastewater treatment can be used for biofuel production as well as the generation of fertilizers, mega-3 fatty acids, therapeutics, nutraceuticals, and other complements like animal feedstock, thus adding to the economic sustainability of the wastewater treatment industry (Saad et al. 2019). Moreover, the industrial, agricultural, as well as domestic wastewaters contain nutrients at high rates that induce the growth of the microalgae. This minimizes or even can eliminate the need for the addition of more nutrients and organic carbon in the waterbody to be treated therefore reducing its cost. Microalgae have shown to be more suitable than other microorganisms tested for the bioremediation of the wastewater. This is because nutrients like nitrate, ammonia, phosphate, and other trace elements present in wastewater are essential for the growth of the microalgae (Salama et al. 2017). Both marine and freshwater algae have been tested for wastewater treatment with freshwater algal strains to have better efficiency in nutrient removal than the marine ones even though the marine ones showed higher growth rates (Aravantinou et al. 2013). Among the many algal species being utilized for the phycoremediation of wastewaters, *Chlorella* and *Scenedesmus* species are the ones used the most than others (Álvarez-Díaz et al. 2017).

Although microalgae grow sufficient in wastewaters, the nutrients usually do not match the optimal levels required for the optimum algal growth during the phycoremediation of the waterbody. To accommodate for this, two strategies are used alone or in combination. The one implies the utilization of specified trained algal species that adapts to the wastewater and the second is the modification of the wastewater to match the algae's growth conditions (Li et al. 2019). Several factors can affect the algae growth during the treatment thus limiting the efficiency of the treatment. Those can be abiotic, biotic, chemical, physical, and mechanical-operational factors of the treatment (Larsdotter 2006). Regulation of those factors can improve the wastewater treatment enhancing algae growth.

Wastewater phycoremediation systems

Open pond systems

Two systems can be implemented for water treatment for the regulation of the factors affecting algal growth: the open system (open ponds) and the closed one. Open pond systems are used for commercial-scale algae growth. Those can be natural basins like lagoons, lakes, and ponds, or artificial ponds (Ugwu et al. 2008). When it comes to open pond systems those are divided into non-stirred and stirred ponds. Non-stirred ponds are more economical and easier to manage but they are prone to algae predation by zooplankton, mixed algal populations, and potential growth of pathogens affecting the algae growth (Chaumont 1993). An open pond without stirring puddle can reach the removal of chemical oxygen demand, ammonia, and P at a rate of 87.93%, 98.17%, and 96.87, respectively, from municipal wastewater, Table 1 (Ting et al. 2017). The advantage of the stirred pond is that provides aeration, better light, and nutrients distribution to the algae thus providing enhanced algal growth (Molazadeh et al. 2019).

Table 1 Non-stirred and stirred raceway systems characteristics

Pond type	Operation mode	Wastewater source	Microalgae	Aeration/L min^{-1}	Biomass production/mg (L day)$^{-1}$	Removal %
Non stirred raceway	Lab-scale, batch system	Municipal wastewater	*Chlorella pyrenoidosa*	1.5	–	COD: 87.93 NH_4–N: 98.17 PO_4^{3-}–P: 96.87
Puddle stirred raceway	Semi-continuous, pilot scale	Municipal wastewater	*Scenedemus* sp.	20	$(4 \pm 0) - (17 \pm 1)$ g (m^2 day)$^{-1}$	COD: 84 ± 7 TN: 79 ± 14 TP: 57 ± 12

COD chemical oxygen demand, *TN* total nitrogen, *TP* total phosphorous (Ting et al. 2017)

High rate algal pond

A raceway or high rate algal pond (HRAP) is the most common stirred pond system used for wastewater treatment first introduced during the late 1950s for wastewater treatment (Oswald and Golueke 1960). They are ecologically beneficial as they have a low carbon footprint in comparison with other water treatments, they reduce the emissions of greenhouse gasses and the algal biomass produced can be used for biofuels production, animal feedstock, nutraceuticals, and others (Saad et al. 2019). Still, despite the economic benefits that can be obtained from the processed harvested algal biomass the actual cost of harvesting the algae in the HRAPs may be a major problem. In many cases, the harvest of the algal biomass is achieved via sedimentation with flocculation. This process is aimed at when the paddles of the pond are stopped from stirring the water. Moreover, growing algal species such as *Chlorella*, *Euglena*, *Chlamydomonas,* and *Oscillatoria* that are resistant to sinking is not desirable in the ponds system (Sen et al. 2013). The most common algal species that can be cultivated in a raceway pond are *Spirulina*, *Dunaliella,* and *Haematococcus* although *Chlorella* has also been reported (Ting et al. 2017). HRAP retrofits making it a cost-effective system, and it is cost-competitive for new waste treatment facilities (Craggs et al. 2014). HRAPs are large shallow-water basins. Their depth does not go further than 25–30 cm, while they have a paddlewheel that stirs the waterbody usually at a speed of 0.15–0.30 m s^{-1}. Paddlewheel selects for colonial algae, which are outcompeted in facultative ponds as the colonies settle faster than the unicellular algae in unstirred water bodies. The HRAP has a retention time between 3 and 4 days during summer times and 7–9 days in winter. The shallow of the pond system together with the stirring ensures good light, CO_2 diffusion, and nutrients distribution. In some cases, CO_2 is added into the waterbody to increase algae productivity (Park and Craggs 2011) (Fig. 1). The addition of CO_2 can double the productivity of the wastewater treatment reaching up to 16–20 g m^{-2} day. Algae photosynthesis throughout the day can cause supernaturation of dissolved oxygen with concentrations that than reach over 20 g m^{-3} which promotes the degradation of organic compounds via the bacteria. The CO_2 supply also helps to maintain the pH of the pond water at an optimum of 7.5–8.5. HRAPs provide better disinfection of wastewater in comparison with treatment ponds as the shallows of the pond allow perpetration of high light intensity inactivating fecal microbes. The algae biomass in a HRAP typically is of 70–90% and the yearly productivity can reach up to 30 t ha^{-1} y (ash free dry wt) in dry summer climates. A maximum loading rate of 100–150 kg BOD_5 ha^{-1} day (BOD_5 per hectare per day) can be achieved in a HRAP.

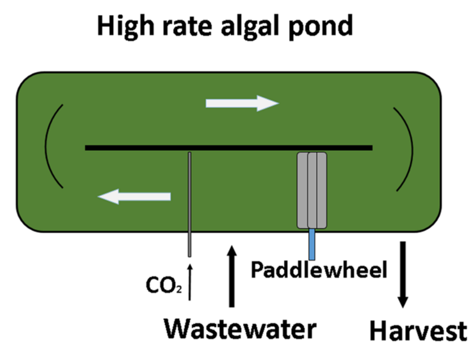

Fig. 1 High rate algal pond raceway with a paddlewheel driving the wastewater and additional CO_2 supply. The arrows indicate the circular motion of the wastewater in the pond

A high rate algal pond system is comprised of several ponds connected to the HRAP. After the HRAP, algal settling ponds are utilized to enable natural settling of the algal biomass produced in the HRAP. The removal of colonial microalgae that are predominant in the HRAP, such as *Micractinium* sp., *Actinastrum* sp., *Pediastrum* sp., and *Dictyosphaerium* sp., is usually achieved by the natural settling of the algae into settling ponds or shorter fermentation time (also known as hydraulic retention time) algal harvest tanks. The removal of the algae can be improved by bioflocculation of the algal colonies with the addition of the CO_2 in the HRAP. Algal harvesting tanks can also be utilized to remove the excess algal biomass and use it for the generation of other products. The ponds are designed to promote gravity settling via the utilization of lamella plates and secondary thickening of settled algae to 1–3% solids (Craggs et al. 2014). After the harvesting, the water goes through a sterilization method that can be via chlorine, ozone (ozonation), membrane filtering, or ultraviolet light (Mandeno et al. 2005) (Fig. 2).

The advanced integrated wastewater pond system

An evolution of the HRAP is the advanced integrated wastewater pond system (AIWPS). This is comprised of three ponds connected to an HRAP. Just before the HRAP, the advanced facultative pond, bearing a digester pit on its bottom, is located. Following the HRAP, an algal settling pond is located where the majority of algae produced in the HRAP is removed. Finally, a maturation pond is located after the settling pond, for solar and biological reduction of pathogens (Mines and Lackey 2009) (Fig. 3). AIWPS is improved to treat large volumes of industrial and domestic wastewater, but the design, construction, and maintenance need expert skills the process is rather complicated and an energy source is also required for the operation of the AIWPS. The high construction and maintenance cost and the need for expert

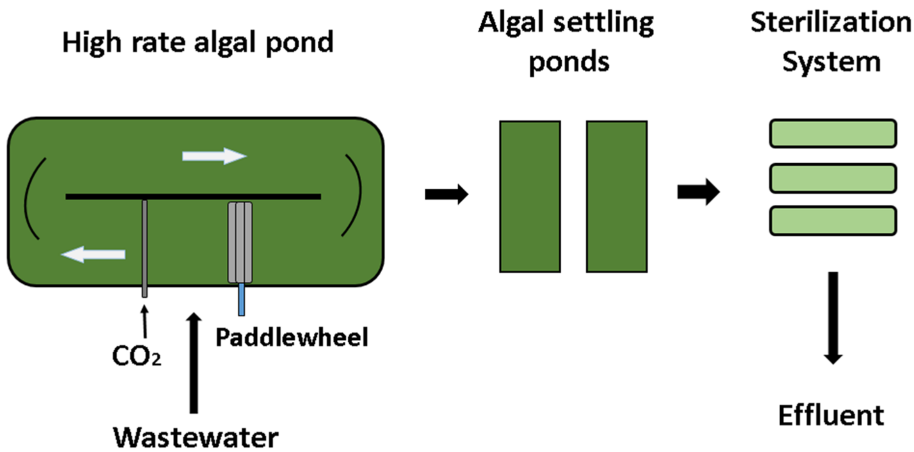

Fig. 2 High rate algal pond system comprised of the high rate algal pond module, the algal settling ponds, and a water sterilization system. The white arrows indicate the circular motion of the wastewater in the high rate algal pond

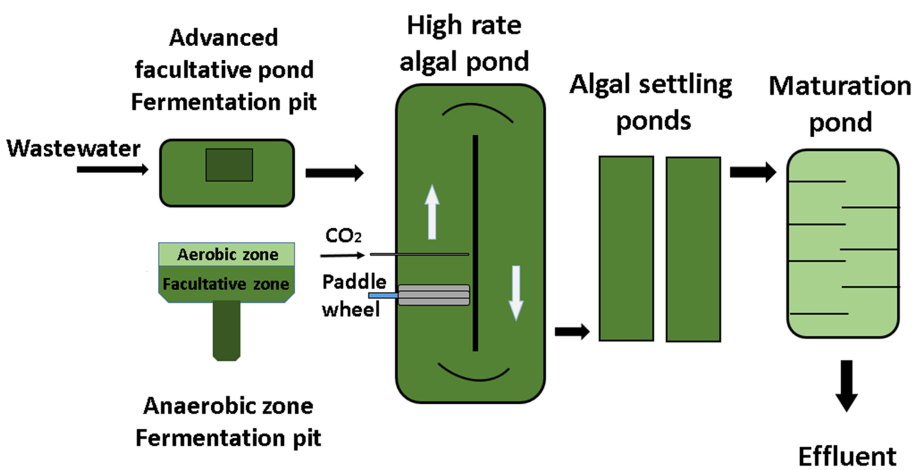

Fig. 3 The advanced integrated wastewater pond system is comprised of a series of ponds. From 4 to 6 m in depth, the advanced facultative pond has a fermentation pit. Three zones are formed in the pond. A top aerobic zone, a middle facultative zone, and at the fermentation pit an anaerobic zone. A high rate algal pond is connected to the facultative pond. It feeds the algal settling ponds where the algal biomass produced in the high rate algal pond is removed. At the end of the treatment follows the maturation pond for further reduction of the pathogens in the water

personnel for operation make the AIWPS system a great challenge for some developing countries.

Waste stabilization pond systems

Waste stabilization pond systems are non-stirred large shallow earthen basins, comprising at any one location one or more series of anaerobic, facultative, and depending on the effluent quality required, maturation ponds (Alexiou and Mara 2003), or several such series in parallel (Abdel-Raouf et al. 2012) (Fig. 4). The bioremediation of the wastewater is achieved via the natural process of algae and bacterial in the basins (Abdel-Raouf et al. 2012). The algae generate oxygen from water as a by-product of photosynthesis. This oxygen is utilized by the bacteria as they aerobically bio-oxidize the organic compounds in the wastewater. Waste stabilization pond systems utilize only sunlight energy and are quite efficient in removing pathogens from the wastewater body (Sunday et al. 2018). Their produced effluents are very suitable for reuse in agriculture and aquaculture. The anaerobic ponds in the waste stabilization pond systems are the smallest units in the series of ponds. The size of such pond is expressed in grams of BOD_5/day for each cubic meter of the pond volume. Relative to their design temperature, the anaerobic ponds can receive a volumetric organic load of 100–350 BOD_5/m^3 day. Their depth is between 2 and 5 m with the most common depth to vary between 3 and 4 m. In warm climates, the anaerobic ponds are very efficient. At 20 °C a pond can achieve around 60% BOD_5 removal and at temperatures of 25 °C BOD_5 removal can go over 70%. A retention time of a day is sufficient to remove $BOD_5 \leq 300$ mg/l at 20 °C and above. The facultative ponds can be of primary or secondary nature. Primary facultative ponds receive the wastewater (Fig. 4(1)) while secondary

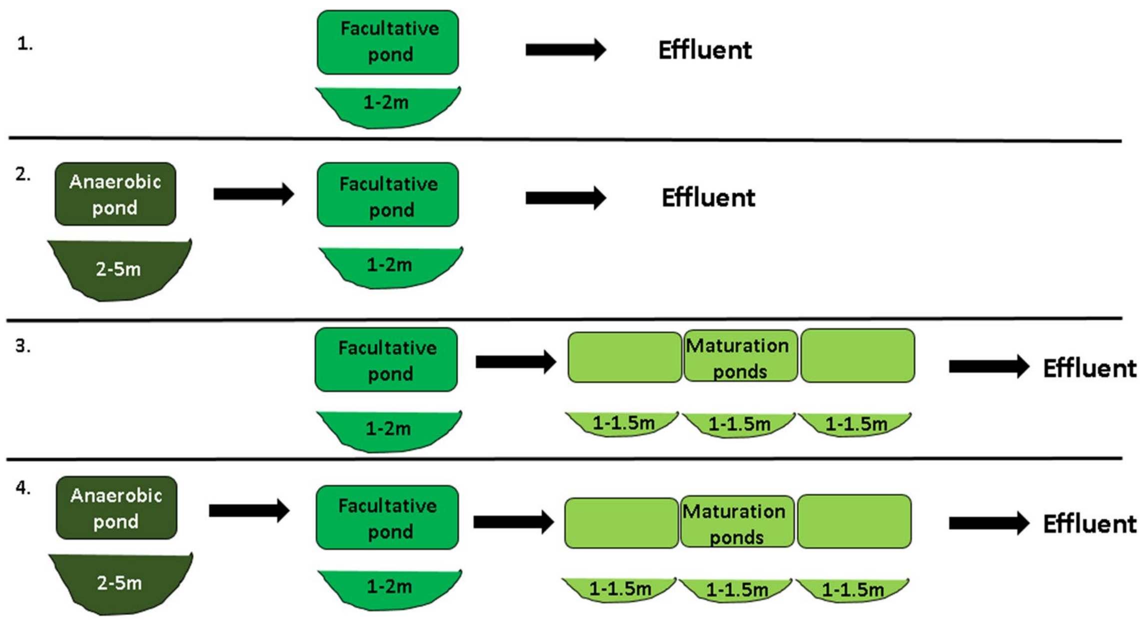

Fig. 4 The waste stabilization pond systems include one or a series of ponds according to the effluent quality required. Arrangements can be (1) Only one facultative pond (1–2 m deep). (2) One anaerobic (2–5 m deep) and one facultative pond. (3) One facultative and a series of maturation ponds (1–1.5 m deep). (4) One anaerobic, one facultative, and a series of maturation ponds. WSPs can have more than one facultative pond accepting effluent from the anaerobic pond

facultative ponds receive wastewater effluent from anaerobic ponds (Fig. 4(2)). The most common depth of the facultative ponds is 1.5 m but they can range from 1 to 2 m. Usually the surface organic load that is used for a facultative pond is ranging between 80 and 400 kg BOD_5/ha day. The concentration of algae in the pond is in the range of 500–1000 µg chlorophyll-a per liter. The dissolved oxygen in the pond can reach up to 20 mg/l in supersaturated conditions, and a pH of 9.4 removing coliforms and viruses from the wastewater (Peña and Mara 2004). In the primary facultative ponds, the removal of the BOD_5 can be up to 70% of unfiltered basis or 90% and more on a filtered basis, i.e., the filtration of the sample before the BOD_5 analysis. The maturation ponds of the waste stabilization pond systems receive the influence from the facultative ponds (Fig. 4(3), 4(4)). Their depth ranges from 1 to 1.5 m with the most usual depth being that of 1 m. Less than 1 m in depth results in rooted macrophytes growth allowing for mosquito breeding. The algal population is more diverse than in the facultative ponds and it increases along with the pond series. A small removal of BOD_5 is achieved in the maturation ponds. A significant contribution is related to the removal of nitrogen and phosphorus from the wastewater. In a waste stabilization ponds system, the nitrogen removal can be 80%, while above 90% is the removal of ammonia, subject related to the number of maturation ponds in the system. The removal of phosphorus is usually about 50%. Due to low maintenance cost and simple design and operation (manually raked screens and manually cleaned constant-velocity grit channels), waste stabilization pond systems are most appropriated for domestic and municipal wastewater treatment in developing countries. Their operation is also particularly suited to tropical and subtropical countries since sunlight and ambient temperature are key factors in their process performance (Sunday et al. 2018). One important thing about the maintenance of the waste stabilization pond systems is the removal of the scum from the facultative and maturation ponds. If not removed scum can cover a large part of the pond impairing algal photosynthesis making the pond turn anoxic. In the anaerobic ponds, sludge needs to be removed when they are around one-third full of sludge. Facultative ponds store any sludge for their design life, which is a significant operational advantage (Peña and Mara 2004).

Closed systems for wastewater bioremediation

Closed systems, like the tubular, the Flat Panel, and the plastic (polyethylene) bag photobioreactors, have been developed in an attempt to better control the factors that affect the efficiency of the algal growth. Photobioreactors can make use of artificial light or natural sunlight. They utilize transparent tubes, containers, or sleeves and have been developed to overcome the practical and biological limitations of the open systems (Chaumont 1993). The tubular system is currently the one that is used on a large scale for microalgae-based wastewater treatment. The design of the tubes can be that of a helix, horizontal, or vertical arrangement (Chisti and from Microalgae 2007) (Fig. 5(1)). Tubes diameter can be from 10 to 60 mm with a length that can reach several hundred meters. Although they have a large surface-to-volume ratio and a continuous culture process there is an uneven biomass transfer that results in an inhomogeneous distribution of temperature and CO_2 resulting in the accumulation of dissolved oxygen. Moreover, it is difficult to clean the tubes from surface biological deposition. Tubular systems are hard to scale-up and are uneconomic for commercial use (Ting et al. 2017). The other closed system design, the Flat Panel, is comprised of a transparent vessel that can be of glass, polyethylene film polycarbonate, or Plexiglas with a thickness of 5–6 cm to allow light penetration in the waterbody (Marsullo et al. 2015). The panels of the system can be arranged in adjacent or parallel plats to avoid self-shading and at an appropriate orientation to entrap the solar energy (Fig. 5(2)). Even though in a closed system it is easier to control the factors affecting the efficiency of the algal growth, therefore, the treatment efficiency, open systems, like lagoons, artificial lakes, reservoirs are preferred to the closed ones as it is simple to construct and maintain, are cost-efficient and do not require expert personnel for operation (Norsker et al. 2011). Moreover, even though in general tubular photobioreactors do perform better in comparison with open systems regarding temperature, pH, mixing, and biomass, there are problems with toxic accumulation of oxygen, overheating, adverse pH, and CO_2 gradients as well as high maintenance cost (Mata et al. 2010). Column photobioreactors are another configuration where the photobioreactor is constructed in vertical columns. Two configurations of column photobioreactors are available. The one that encompassing airlift and the one the utilizes a bubble column (Ngo et al. 2019). The airlift is a type of bubble reactor. It contains an internal draft tube that promotes gas–liquid mass transfer and mixing. Airlift reactors have been largely used for algae cultures (Duan and Shi 2014). In the airlift configuration, there is no need for a mixing apparatus as the mixing is achieved via the injection of air into the compartment. Similarly, in the bubble columns, the mixing is achieved via the bubbles in the column. The size of the bubbles affects the hydrodynamics in the reactor and determines the mass transfer. The diameter of the tubes ranges from 10 to 60 mm and the length can reach several hundred meters (Ting et al. 2017). It has been reported that in airlift column photobioreactors, the growth rate achieved is higher compared to the bubble columns photobioreactors (Chiu et al. 2009). One of the main limitations of the

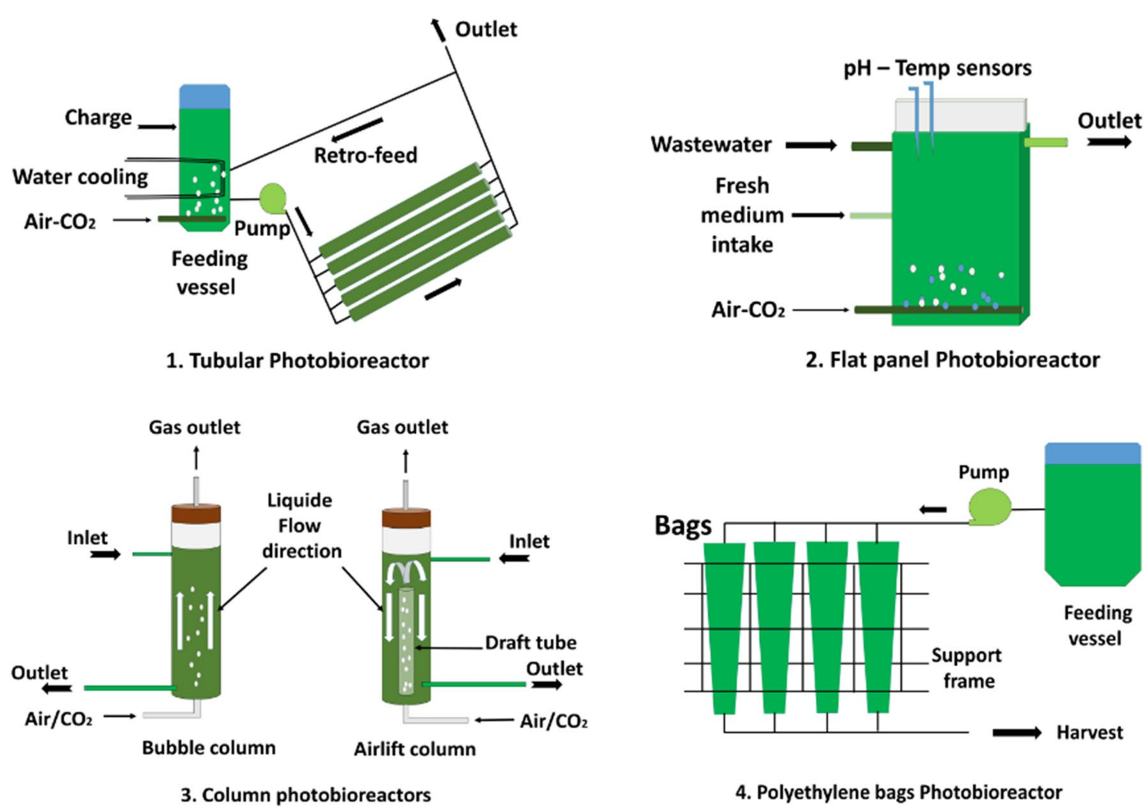

Fig. 5 Most common closed system photobioreactors (1) Tubular photobioreactors. (2) Flat-panel photobioreactor. (3) Column photobioreactors, bubble, and airlift systems. (4) Polyethylene bags photobioreactor

column photobioreactors is the irregular mass transfer in circular directions that can inhomogeneous distributions of temperature and CO_2 and can lead to an accumulation of dissolved oxygen (Ting et al. 2017). Moreover, it is difficult to clean the tubes from residual material that can block the light penetration in the tubes. Scaling up for large amounts of wastewater phycoremediation is also a challenge, as it will require a large area for the installation. There are methods to avoid fouling in the reactor but this will dramatically increase the maintenance cost (Ting et al. 2017). Column photobioreactors have a simple design and can combine with other systems, especially membrane ones creating hybrid systems (Ngo et al. 2019) (Fig. 5(3)). Photobioreactors using polyethylene bags are also utilized because of their low cost, transparency, and sterility of the bags at the time of starting cultivation. The arrangements of these photobioreactors can have the form of vertical bags, hanging individually or in parallel series mounted on a support. A pump drives the flow of liquid through the bags, feed air inside the bag, and provide medium (Płaczek et al. 2017). These arrangements are considered to have a good surface area-to-volume ratio (Fig. 5(4)).

The yield of biomass between the different systems vary. According to the research literature, a flat panel photobioreactor has the highest biomass concentration of 7.5–96.4 g/l, followed by the column photobioreactor with 19.78 g/l. The other photobioreactor systems have shown less biomass yield with a yield value of around 4 g/L. In comparison with studies among the tubular and the bubble column photobioreactors, regarding the biomass yield, the tubular one was 7 g/l while the bubble one gave a biomass yield ratio of 0.41 g/l. Regarding the productivity of the two systems, the tubular system had productivity of 0.55 g/l day while the bubble column was reported to have 0.12 g/l day. Regarding N and P removal a flat panel photobioreactor that bears a glass mesh supported by a nylon membrane (twin-layer photobioreactor) could remove 70% of N and 99% of P from wastewater (Table 2). These are at least twice higher values than an open pond system can achieve. The twin-layer photobioreactor could remove 90% or more of the pollutants in municipal wastewaters within 9 days. In tubular photobioreactors, N and P removal has been reported to a value of around 91% and 95%, respectively. Experiments involving the treatment of effluents from an urban wastewater treatment plant gave removal efficiencies of 89.7 and 86.7% for N and P, respectively. These rates were higher than the rates from an algae pond that was 65.1 and 58.7% for N and P, respectively (Ngo et al. 2019). Polyethylene bags photobioreactors have also a very high efficiency in pollutants removal. The photobioreactors have polyethylene bags that bear only microalgae without any bacteria. Chlorella strain is among the most popular microalgae used. Treatment of pig effluent in 20L transparent polyethylene bag with 4.4 l/m aerations resulted in the removal of 91.8%, 54%, and 65.4% of ammonia nitrogen, nitrate, and phosphorus, respectively. Experiments treating carpet manufacturing wastewater utilizing tubular (100 l) and polyethylene bags (20 l) photobioreactors showed the bags gave higher biomass production than the tubular photobioreactor (Ting et al. 2017).

Although in closed systems it is easier to control the abiotic factors and therefore to optimize the phycoremediation process, the building, maintenance cost, complicated operation, and difficulties in scaling-up make them unsuitable for large-scale wastewater treatment.

There are attempts for hybrid designs blending the open pond and closed systems. Usually, to achieve that blend a cover is placed over an open pond in an attempt to increase control over the environmental conditions. Other designs used covered channels lined with plastic feed with media (Keeler et al. 2010). New design multi-technology hybrid systems involve the utilization of membrane photobioreactor and microalgae biofilms. Those designs combine a conventional photobioreactor with a membrane or biofilm process, respectively. The microalgae biofilm reactors utilize

Table 2 The removal efficiency of photobioreactor systems

Type of PB	Wastewater	Algae species	Removal efficiency		
			TN	TP	COD
Tubular	Olive washing	*Sphaeropleales*	–	–	85.86 ± 1.24
Flat panel twin-layer	Municipal	*Halochlorella rubescens*	70–99	70–99	–
Airlift column	Bio-industrial	*Chlorella sorokiniana*	100	100	–
Bubble column	Synthetic	*C. vulgaris*	60–99	100	–
Column	Synthetic	Algae-bacteria consortium	60.4–70.5	93.2–96.4	95.5–96.7
Soft frame bag	Agricultural run-off	*Pediastrum* sp., *Chlorella* sp., *Scenedesmus* sp., and *cyanobacteria Gloeothece* sp	Not determined	Not determined	73% tonalide 68% galaxolide 61% anti-inflammatory compounds

COD chemical oxygen demand, *TN* total nitrogen, *TP* total phosphorous (Ngo et al. 2019) an extracellular polymeric substance that surrounds a consortium of microorganisms comprising both phototrophs and chemotrophs and microalgae that are grown on a solid surface with different sharp and structure (Li et al. 2019). In comparison with the HRAP, it has been reported that the phototrophic biofilms can offer an additional advantage in terms of time and cost savings involved in biomass accumulation and harvesting as the removal of the microalgae biomass can be achieved by simply scraping the film of the growth support (Guzzon et al. 2019). Similar to the Biofilm reactors the membrane photobioreactor utilizes a membrane that holds the algae immobilized during their growth. One major operational and cost-related challenge in the membrane photobioreactor is membrane fouling (Luo et al. 2017) which results in a reduction in membrane permeability. Membrane fouling and water flux decline are the most important issues in membrane bioreactors. Membrane fouling is affected by the hydraulic retention time (Mohan et al. 2011), and the solids retention time relates to the growth rate of the microorganisms and effluent concentrations in the wastewater. The hydraulic retention time and the solids retention time together with other parameters affecting the algal growth like temperature, pH, light, and aeration should be carefully taken into consideration during the design of a membrane photobioreactor (Clara et al. 2005).

Factors affecting the wastewater treatment via algae

Light intensity

Algae are phototrophic organisms. They utilize light to produce chemical compounds needed for their growth. The absorption of nutrients for growth is enabled by the process of photosynthesis, which is stimulated by the supply of inorganic carbon, light, and temperature (Whitton et al. 2015). Light affects the algal growth resulting in alterations in the nutrients utilization efficiency from the waterbody. In closed indoor systems, an artificial light source can be utilized to enhance the photosynthetic activity of the microalgae in the waterbody. Microalgae photosynthetic systems are more efficient in the blue and red regions of the spectrum, 400 and 600–700 nm, respectively, with an effect in the better utilization of nitrogen and phosphorus from the wastewater, with the red light to stimulate the algal growth. Although the utilization of artificial light adds to the cost of the wastewater treatment, the technology of the light-emitting diode that provides a longer lightbulb lifespan in combination with lower cost in electricity consumption makes more prominent the utilization of artificial light sources for increasing the photosynthetic activity of the algae thus enhancing the nutrients uptake from the waterbody (Ibrahim et al. 2014). Developed light-emitting diodes technology with narrow-band wavelengths is considered the best light source for cultivating the algae (Michel and Eisentraeger 2004). Studies have taken place for identifying the light wavelength more suitable for algal growth. Studies on *Scenedesmus* sp. showed an increased removal rate by 45% of phosphorus under a blue light regime of 1.8 mg L^{-1} day^{-1} in comparison with white light (Kim et al. 2013), while a study utilizing *Spirulina platensis* showed that red light increased by 38% the growth rate of the microalgae (Wang et al. 2007). Maximal productivity with *Chlorella vulgaris* has been obtained by exploiting green light (Kubín et al. 1983). Experimental work on high-density algal cultures of *Scenedesmus bijuga* showed that weakly absorbed colors, such as the green one, result in higher photosynthetic efficiency (Mattos et al. 2015). Work on the effect of light colors in the photobioreactors utilizing *Chlamydomonas reinhardtii* showed that blue and red colors are suboptimal for the generation of algal biomass with the highest biomass productivity obtained from the usage of the warm white and yellow light. Yellow light supplemented with blue light gave increased growth and culture fitness (de Mooij et al. 2016).

In open systems light intensity and availability to the microalgae depended on the depth of the open waterbody as in deeper waters, the light intensity is lower. Thick algae cultures also block the light from reaching deeper into the waterbody. Moreover, the presence of other microorganisms can affect the availability of light to the algae. Water agitation is also important as good circulation allows better exposure of the microalgae in the waterbody in the surface light, also prevents the exposure of the algae at the top layer of the water for a long time to the high-intensity surface sunlight reducing the possibility of photoinhibition, damage of the photosystem II by intense light (Murata et al. 2007), which results in the lower photosynthetic ability of the microalgae (Gordon and Polle 2007).

Temperature

Temperature can significantly affect and limit the growth of the algae in open water bioremediation systems (Ras et al. 2013). The optimum temperature of the algae to grow has been reported to be between 15 and 30 °C depending and on the algae species (Singh and Singh 2015). In a closed system photobioreactors exposed to the sunlight, the system also heats up and its temperature can rise over 40 °C. Although cooling systems can be used to reduce temperature to optimum levels for algal growth, this adds to the cost of the wastewater treatment (Eustance et al. 2016). Open systems that are prone to seasonal temperature changes due to the cooling effect produced via the water evaporation usually keep the water temperature lower than 40 °C, subject to the facility's geographic location (Balázs József et al.

2018). As with high temperatures, low temperatures also affect negatively the algal growth. In cold environmental conditions, microalgae are more prone to photoinhibition due to cold stress. In combination with low light intensity and small photoperiods during wintertime, it can make unaffordable the creation of open wastewater treatment facilities in countries with cold climates (Whitton et al. 2015). Another important factor in cold climates is the algal strain origin (Teoh et al. 2013). *Chlamydomonas* species from cold climate zones showed reduced ability in productivity affecting the nutrients uptake thus diminishing the bioremediation process of the wastewater when it was tested in warmer temperature conditions from its natural ones (Aigars and Tālis 2017). To improve the nutrients uptake by the algal cell in cold climates facilities that will keep the temperature during the treatment stable, like a water heating system or greenhouse facilities, can be implemented in an attempt the treatment to carry on throughout the year during both the summer and the wintertime (de la Noüe et al. 1992).

pH value

One other important factor that affects the growth of the microalgae is the pH value. During the wastewater treatment pH increases due to the accumulation of the photosynthetic CO_2 in the water (Chevalier et al. 2000). High pH acts as a disinfectant agent in the water. A pH of 9.2 for 24 h will kill 100% of *E. coli*, most pathogenic bacteria, and viruses (Pearson et al. 1987). The elimination of the *E. coli* from the waterbody had been an indicator of the disinfection of most bacteria and viruses such as *Salmonella*, *Shigella*, *Campylobacter,* and rotavirus. An exception is the *Vibrio cholera* that has different disinfection responses and the use of *E.coli* as a disinfection indicator should be used cautiously when referring to *Vibrio cholera* (Davies-Colley et al. 2003). In open pond systems that are not a controlled environment, it is very challenging to utilize pH alone to control pathogen fluctuations in the waterbody. Other factors together with the pH, like temperature, dissolved oxygen, and solar radiation, must be considered as closely interrelated factors operating in the system that can affect the concentration of pathogens in the system. An increase in radiation for example can directly reduce pathogens in the water or induce the algae metabolism thus increasing the pH and the levels of diffused oxygen that can act synergistic and result in the deactivation of the E.coli pathogen (Rose et al. 2007).

Although high pH can act as a disinfectant agent, high pH values of pH 9 and above can also affect the algal growth thus impairing the wastewater treatment (Larsdotter 2006). Moreover, it has been reported that high pH values can result in microalgae flocculation in the presence of phosphate and divalent cations (Mg^{+2}andCa^{+2}) affecting the treatment efficiency (Vandamme et al. 2012). A high concentration of Ca^{+2} and a pH value higher than pH10 have high flocculation efficiency for the Chlamydomonas (Fan et al. 2017). Appropriate pH values for algal growth have been indicated to be between pH7 and pH 9 (Devaraja et al. 2017). Levels of pH below 8 can be maintained with the addition of CO_2 (Park and Craggs 2010). pH plays a critical role in the regulation of inorganic carbon (Liu et al. 2016) and in stimulating an increase in algae biomass production (Aigars and Tālis 2017).

CO_2

Algae, being a phototrophic organism, require CO_2 to feed their photosynthesis mechanism. They are mostly dependent on the diffusion of the CO_2 to cover their demand for carbon. During the wastewater treatment, the main source of inorganic carbon that is essential for algal growth is the consortia of bacteria that decompose nutrients in the wastewater by aerobic respiration to release the CO_2 that in turn will be utilized by the algae in photosynthesis. CO_2 addition in the wastewater increased the biomass of the algae. Inorganic carbon in the form of HCO_3^- (bicarbonate ions) is another source of CO_2, for the algae have the mechanisms to utilize HCO_3^- and release the CO_2 from the compound. HCO_3^- significantly increases algal growth (Liu et al. 2016). Air can also supply CO_2. Agitation of the water and pH have an important role in the direct diffusion of CO_2 from the atmosphere. It has been shown that the rate of diffusion of CO_2 in the water at a pH10 is 100 times greater than it is in a pH8 (Oswald 1996). Since the CO_2 level in the atmosphere is much lower than the optimum concentration needed for algal growth (Fontes et al. 1987) additional supply of CO_2 in the water with an air mixture of 1–5% CO_2 can maximize the algae biomass (Singh and Singh 2014). Experiments on wastewaters from the mining industry have shown that freshwater macroalgae are prominent candidates for the bioremediation of water contaminated with metals. CO_2 supplementation in the waterbody increased the biomass production of the algae during the treatment, although after a while there was a decrease in production probably due to the toxicity of the metals in low pH or the limitations in the presence of trace elements (Roberts et al. 2013). In HRAPs CO_2 addition can control pH below 8 without affecting the dissolved oxygen levels in the pond while it can increase the removal of the soluble organic compounds up to 95% (Park and Craggs 2010). Even though the supplementation of CO_2 has a positive effect on algal biomass increase, the additional cost that is required during the treatment can result in the sacrifice of the CO_2 supplement to the phycoremediation treatment (Larsdotter 2006).

Wastewater phycoremediation

Nutrients removal

Algae can take up various kinds of nutrients like nitrogen and phosphorus. The concentration of a nutrient inside and outside the algal cell as well as the diffusion rate through the cell wall affects their uptake from the algae during the treatment (Borowitzka 1998). Concentrations and ratios of nutrients and metabolites can affect water treatment and algal growth.

Algae need nitrogen and phosphorus in their growth. Phosphorus is essential for the synthesis of nucleic acids, phospholipids, and phosphate esters in the cells while nitrogen bounds to the proteins in the algal cell that comprises between 45 and 60% of dry weight. They utilize various organic compounds containing nitrogen and phosphorus from their carbon sources. Utilization of those compounds by the algae results in nutrients removal from the wastewater, a process that can last from few hours to few days (Lavoie and De la Noüe 1985). Domestic, industrial, and agricultural wastewaters are already rich in nutrients content and the need for the addition of more nutrients is limited. Still maintaining a ratio among certain elements can improve the treatment. As an example, the ratio of carbon to nitrogen (C/N) and nitrogen to phosphorus (N/P) has an important role during wastewater treatment, as their ratio affects the absorption of the nutrients. Since bacteria and algae can utilize organic carbon via heterotrophic or mixotrophic metabolism, carbon can become a limiting factor for algal growth in wastewater treatment facilities (Su et al. 2011). Ammonia (NH_4^+), nitrite ($N02^-$), or nitrate ($N03^-$) are the forms in which nitrogen (N) is found in the wastewater while phosphorus (P) exists in the form of phosphates ($P04_3^-$). In the untreated wastewater, the amounts of N and P are between 10 and 100 mg L^{-1} (de la Noüe et al. 1992). After the secondary treatment, these amounts are dropping to 20–40 mg L^{-1} for the N and 1–10 mg L^{-1} for the P, respectively (McGinn et al. 2011). These concentrations of N and P are suitable for microalgae growth. In the wastewater, the ratio of N to P is 11–13 (Christenson and Sims 2011). In the macroalgae, this ratio is 11.2 (Chisti 2013) that is similar to the ratio found in the wastewater. The widely accepted N:P ratios for microalgae growth are 16 (Cai et al. 2013) making the wastewater a good medium for the bioremediation of the water with microalgae. The use of microalgae for wastewater treatment was under consideration since the late 1960s and early 1970s. In the late 1970s, the *Chlorella salina* microalgae were utilized for the removal of nitrogen and phosphorus from sewage with high sanity (Chan et al. 1979).

As an attempt to improve nutrients removal, co-immobilization systems bearing microalgae and growth-promoting bacteria have been tested. Chlorella species have been co-immobilized with *Azospirillum brasiliense*, a bacterium that can enhance the growth of the immobilized algae in Ca-alginate beads. The co-immobilized system has given improved nutrients removal capabilities with 100% ammonium, 15% nitrate, and 36% phosphorus removal rates in comparison with the solo immobilized algal cells with rates of 75% ammonium, 6% nitrate, and 19% phosphorus removal, respectively (Moreno-Garrido 2008).

Heavy metals removal

Heavy metals found in domestic wastewater include As, Cd, Cr, Cu, Pb, Hg, and Zn (Gupta and Bux 2019). Heavy metals and non-natural elements are known to be detoxified/ transformed/or volatilized by algal metabolism. Heavy metals like Cu, Ni, Mn, Co, and Zn are important micronutrients necessary for the growth of the plants but via bioaccumulation can have negative effects on humans and animals alike. Heavy metals cannot be degraded. They can accumulate via the food chain inside the living organisms where can directly interfere with metabolic processes or be converted into more toxic forms (Malik et al. 2019). Affects for example related to liver fibrosis and kidney damage by the Cu, hematopoietic system disorders, pulmonary disease, and nervous pulmonary system disorders by the As, or kidney disease, affects the circulatory and nervous system, as well as the fetal brain by the Pb. These heavy metals are classified into three categories. The precious metals that involve Au, Pd, Pt, and Ru, the radionuclides U, Ra, Am, and Th, and the toxic metals Zn, Ni, Ag, Cu, Cr, As, Sn, Co, and Pb (Pavithra et al. 2020). Algae are among the biomaterials that are used for controlling heavy metal ion pollution, like the anaerobically digested sludge the fungi, hemp-based biosorbents, and bacterial biomass (Malik et al. 2019). Several algae species have been tested for their ability to remove metals from the waterbody. Those include freshwater green algae like *Chlorella* spp., *Cladophora* spp., *Scenedesmus* spp., and *Chlamydomonas reinhardtii*, brown algae like the *Sargassum natans*, *Fucus vesiculosus*, *Ascophyllum nodosum*, and *Laminaria japonica*, and blue-green algae like *Microcystis aeruginosa* and *Oscillatoria* (Mehta and Gaur 2005). The algal biomass can be used as an alternative means for the absorption of heavy metals from the wastewater. Algae's fast growth rate, the ability to grow in wastewaters, their low requirements in nutrients concerning other organisms, their robustness in growing under harsh environmental conditions (Abou-Shanab et al. 2011), then no need for land space and irrigation to grow, and the production of products from the generated biomass as additional means of reducing the wastewater treatment cost makes them prominent candidates (Salama et al. 2017). Different algal species have different rates of heavy metals removal. As an example, 91% of Cu^{2+} and 98% of Ca^{2+} was removed from municipal wastewaters utilizing the *Spirulina* sp. microalgae (Anastopoulos and Kyzas 2015). The utilization of *Chlorella minutissima* resulted in the removal of 84% of the Cu^{2+} from the waterbody. Respectively, other heavy metals like Zn^{2+}, Mn^{2+}, and Cd^{2+} had a removal efficiency of 62, 84, and 74% efficiency, respectively (Yang et al. 2015). *Chlorella*, *Scenedesmus,* and *Chlamydomonas* species are effective in the removal of heavy metals, toxic organic compounds, and secondary pollutants from wastewaters bearing several initial concentrations of these compounds (Gao et al. 2016). Different species have different tolerance levels and survival rates in wastewaters bearing high concentrations of heavy metal (Kotrba 2011) as algae accumulate metals via different cellular mechanisms. The successful removal of heavy metals can depend on the species, the nature of the wastewater, the types of the ion metals present as well as the presence of dead algal cells in the waterbody. As live microalgal cells utilize heavy metals via the processes of bioaccumulation and biosorption, dead algal biomass can also remove heavy metals from wastewaters via the process of biosorption but with much less efficiency than the living ones (Salama et al. 2019). In addition to free cells, immobilized microalgae cells have been tested for the removal of heavy metals from aqueous solutions. Different methods have been used to immobilize microorganisms on carriers. These methods involve adsorption, covalent binding, encapsulation, and entrapment. Entrapment of the microalgae *Isochrysis galbana* into alginate gel has been tested for the removal of chromium (III) from aqueous solution with achievement of 90% removal rate in a time period of 4.5 h. *Isochrysis galbana* showed a maximum experimental absorption of chromium of 335.27 mg $Cr(III)g^{-1}$ of dry algal biomass making it a potential biosorbent for the removal of chromium. Entrapped algal cells of *Pediastrum boryanum* in alginate and alginate–gelatin beads showed biosorption capacities of Cr(VI) at the range of 90% removal in 90 min with achieving biosorption 17.3 mg/g as free cells and 29.6 mg/g as immobilized cells in alginate–gelatin matrix showing that immobilized cells had better biosorption than the free ones. On the contrary, the removal of uranium from aqueous solutions tested among free and immobilized *Chlamydomonas reinhardtii* algae cells, in carboxymethyl cellulose beads revealed that free cells had better biosorption capabilities that the immobilized ones with 337.2 and 196.8 mg/g, respectively (Bouabidi et al. 2019). Similarly to the *Pediastrum boryanum*, the green algae *Enteromorpha prolifera* that had been tested in a batch and in a continues system for the biosorption of Ni ions was found to have a biosorption of 65.7 mg/g, while the waste biomass entrapped into silica-gel matrix have higher biosorption capacity of 98.01 mg/g in relation to free cells. These results related to the biosorption capabilities of the *Enteromorpha prolifera* showed that the silica-immobilized waste biomass has the potential of being a cost-efficient sorbent for the removal of Ni ions from synthetic and real wastewater (Mudhoo et al. 2012). The biosorption abilities of microalgae are related not only to the species but also to the contaminant and the presence of the algae as free or immobilized cells into a matrix, factors that have to be taken under consideration when designing wastewater treatments.

Nowadays together with identifying the proper algal strain for the type of wastewater to be treated, molecular genetics has also been recruited for the development of new genetically modified algal stains that will have improved traits and capabilities for the removal of the heavy metals from the wastewaters (Apandi et al. 2019).

Biochemical oxygen demand reduction

High levels of biochemical oxygen demand can exhaust the oxygen in the water resulting in the suffocation of the fish and create conditions for anaerobiosis in the water. Biochemical oxygen demand removal is a primary target when it comes to wastewater treatment. Since microalgae produce oxygen via the photosynthesis procedure, they can relieve biological oxygen demand in the wastewater. The removal of the phenolic compounds also reduces the biochemical oxygen demand in the waterbody. In experimental procedures, it has been shown that microalgae like the *Chlorella pyrenoidosa*, *Chlorella kessleri,* and *Spirulina* sp. have the ability to remove phenolic compounds from water (Zhang et al. 2020) and can be prominent species for the removal of phenols. Although, in wastewater treatment, the removal of the phenolic compounds by algae may be of a challenge as microalgae can only biodegrade phenol under limited carbon source conditions under which they utilize phenol as an alternative carbon source, wastewaters are usually rich in carbon sources for the algae to utilize thus reducing the potential use of phenol compounds as an alternative energy source.

Algae contribution in wastewater disinfection

Bacteria such as *Salmonella* and *Shigella*, as well as protozoa and viruses, are pathogens of concern in wastewater. The degree of the removal of total coliforms in the waterbody is valuing the efficiency of the disinfection of wastewater. Factors that are favorable for algal growth are unfavorable for the survival of coliforms (Moawad 1968). Utilization of the microalgae *Scenedesmus obliquus* in sewage effluent in a high rate pond systems showed total removal of *E. coli* within 4 days due to the high pH values in the pond system being higher than pH9.4, while it was reported that 2 days at pH 11 was suitable for the total removal of *E. coli* from the high-rate algal ponds (Sebastian and Nair 1984). For the process of phycoremediation waste stabilization pond systems perform more effectively than conventional sewage treatment systems (Shelef et al. 1977). It has been reported that in the stabilization ponds a significant amount of coliform microorganisms can be removed from wastewater reaching up to 99.6% (Abdel-Raouf et al. 2012). A similar rate of coliform removal at 99% has been reported from the HRAPs (Colak and Kaya 1988).

Microalgae harvest

Harvesting of microalgae is vital for wastewater treatment to remove the nutrients and biochemical oxygen demand from the water (Borowitzka 1998). Even though harvesting effectively can be accomplished by several methods like filtration, centrifugation, chemical flocculation, or immobilization systems such as Biofilms (Li et al. 2019) and membrane photobioreactor (Luo et al. 2017), the cost of these procedures is considerably high as such methods may be too difficult or costly and can end up being the most expensive part of the wastewater treatment (Sen et al. 2013).

Discussion

Wastewater treatment focuses on the reduction in the biochemical oxygen demand, organic, inorganic, and artificial elements like large amounts of ammonium, bicarbonate, phosphate, potassium, sulfur, heavy metals, pesticides, and a great variety of pathogenic human and animal bacteria from the wastewater. The idea of using algae for wastewater treatment was established in the mid-1940s (De Pauw and Van Vaerenbergh 1983). The microalgae can remove the biological and chemical compounds during the phycoremediation process, which is the bioremediation of wastewater using algal species (Pavithra et al. 2020). Among the several algae species, *Euglena*, *Oscillatoria*, *Chlamydomonas*, *Scenedesmus*, *Chlorella*, *Nitzschia*, *Navicula,* and *Stigeoclonium* were found to be the most tolerant genera to organic pollutants (Palmer 1969), while algae species like *Chlorella*, *Cladophora*, *Scenedesmus*, *Chlamydomonas reinhardtii*, *Sargassum natans*, *Fucus vesiculosus*, *Ascophyllum nodosum*, *Laminaria japonica*, *Microcystis aeruginosa,* and *Oscillatoria* have been tested for their ability to remove heavy metals from the wastewater. *Chlorella* and *Scenedesmus* are the ones used the most in the phycoremediation process of wastewaters (Arbib et al. 2014). In comparison with other chemical treatments, microalgae wastewater bioremediation is cost-efficient and does not leave additional pollution (Hammouda et al. 1995). Moreover, algae can remove the biochemical oxygen demand generated via the process of nutrients decomposition by aerobic bacteria (Orellana et al. 2011). As a means of increasing the cost-efficiency of the phycoremediation the microalgae biomass produced during the wastewater treatment can be used as a source for biofuels production, fertilizers, therapeutics, nutraceutical, mega-3 fatty acids, animal feedstock, and others (Filippino et al. 2015). Microalgae are found in coastal areas, lagoons, seas, and rivers (Ibrahim et al. 2020). The agricultural, domestic, and industrial wastewaters are rich in nutrients at high levels, which induce the growth of the microalgae minimizing or even eliminating the need for supplementation (Karthik et al. 2020). Usually, the amount of those nutrients falls outside the optimal levels for optimal algal growth; thus, some regulation may be needed. Two strategies can be implemented to achieve that regulation. The one implies the utilization of specified trained algal species for the wastewater, while the second one implies the modification of the wastewater to match the algae's growth conditions.

Optimization of wastewater phycoremediation focuses on the improvement in the techniques exploiting the fast-growing rates of the microalgae as well as improving the design and developing new wastewater treatment facilities. Two different systems are used for wastewater treatment: the open and close systems. Open systems comprised of natural or artificial ponds used for large-scale phycoremediation processes. The open systems can utilize non-stirred (waste stabilization pond systems) and/or stirred ponds (HRAPs/AIWPS). Non-stirred ponds are more economical and easier to manage but they are prone to algae predation by zooplankton, mixed algal populations that could affect the algae growth. Stirred systems provide aeration and in some cases, CO_2 supplement, better light, and nutrients distribution thus improving algal growth (Molazadeh et al. 2019). Agitation also helps to reduce the opportunity of photoinhibition, damage of the photosystem II from long-term exposure of the pond's top-layer algae to the high-intensity sunlight (Murata et al. 2007). Closed systems make use of photobioreactors as a means to control the factors affecting the phycoremediation of wastewater. Closed systems include tubular photobioreactors, flat panel photobioreactor, column photobioreactor, and polyethylene bags photobioreactor. Membrane photobioreactor and microalgae biofilms are attempted to generate hybrid systems combining both open and closed systems. In closed systems, the regulation of the factors affecting algal growth (abiotic, biotic, chemical, physical, and mechanical-operational ones) is easier to control but are costly to maintain and require highly skilled personnel to operate. Developments in other fields can help reduce the algae–wastewater systems production and maintenance cost on the phycoremediation in closed and open systems alike. As light intensity affects the algal growth resulting in alterations in the nutrients utilization efficiency from the waterbody, the newest developed light-emitting diode technology is considered the best light source for cultivating the algae. The low heat emission of the light-emitting diode technology in comparison with the incandescent lamps can also help with reducing the cost of energy needed for running cooling systems during the phycoremediation process. The optimal temperature of the microalgae's growth is between 15 and 30 °C. In closed systems, the temperature can exceed 40 °C and cooling must be provided, thus adding to the cost of the wastewater treatment. In open pond systems usually because of the evaporation, the water stays below 40 °C depending and on the geographic location of the facility (Balázs József et al. 2018). pH and CO_2 are also factors that affect the phycoremediation process as they affect algal growth. pH also can act as a disinfectant agent as at high pH values of 9.2 and above for 24 h will kill 100% of the *E.coli* bacteria, most pathogenic bacteria and viruses in the waterbody (Pearson et al. 1987). Similarly in HRAPs (high-rate algal ponds), 2 days at pH 11 are enough for the total removal of the *E. coli* bacteria (Sebastian and Nair 1984).

Algae need nitrogen and phosphorus in their growth. Phosphorus is vital for the synthesis of nucleic acids, phospholipids, and phosphate esters in the cells. The nitrogen is important for the bounds to the proteins in the algal cell that comprises between 45 and 60% of dry weight. Moreover, other trace elements and heavy metal ions present in wastewater are essential for the growth of the microalgae (Salama et al. 2017). Experiments on wastewaters from the mining industry have shown that freshwater microalgae are prominent candidates for the bioremediation of water contaminated with metals. Heavy metals are absorbed by the algae from the extracellular area by bioaccumulation. Algae do not lead to secondary pollution after the utilization of heavy metals or toxic agents. Even dead algal biomass can also remove heavy metals from wastewaters via the process of biosorption although this process is less effective compared to the live algae cells (Salama et al. 2019).

The ability of the algae to use nutrients, heavy metals, hydrocarbons, nitrogen, phosphorus from the wastewaters makes them prominent species for the bioremediation of wastewater (Kumar et al. 2019). Biological treatment of wastewater performs well compared to the chemical ones, as is cost-efficient and does not generate additional pollution, something that the chemical treatments do (Hammouda et al. 1995). Algae have low requirements in nutrients in comparison with the other organisms and provide a cost-efferent means for wastewater treatment. Based on their advantages to other organisms they are classified as prominent candidates in wastewater treatment. New technologies are focusing on the exploitation of algae for wastewater treatment. Besides, molecular methods are implemented in generating novel algal strains with increased capabilities in the phycoremediation process.

The phycoremediation process utilizing open pond systems like the waste stabilization pond systems due to low maintenance cost, simple design, and operation can provide wastewater treatment of domestic and municipal wastewater that is much needed in developing countries, thus improving life quality, and reducing carbon footprint and environmental pollution for the benefit of flora, fauna, and humans alike.

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