WORLD JOURNAL OF PHARMACEUTICAL RESEARCH
SJIF Impact Factor 8.453
Volume 13, Issue 10, 18-36. Review Article ISSN 2277–7105

INTEGRATING MICROALGAE-BASED WASTEWATER TREATMENT FOR SUSTAINABLE ENVIRONMENTAL AND ENERGY SOLUTIONS-A REVIEW

Gonepalli T. D.* and Oroszi T. O.

Department of Pharmacology & Toxicology, Boonshoft School of Medicine, Wright State University, Fairborn, OH.

Article Received on
27 March 2024,
Revised on 17 April 2024,
Accepted on 07 May 2024
DOI: 10.20959/wjpr202410-32212

***Corresponding Author**
Gonepalli T. D.
Department of Pharmacology & Toxicology, Boonshoft School of Medicine, Wright State University, Fairborn, OH.
gonepalli.2@wright.edu

ABSTRACT

Microalgae can grow under various environmental circumstances; they are a potential source of sustainable biomass feedstock for the production of biofuels. The most costly and challenging stage in creating microalgal biofuel is the mass culture of microalgae. Wastewater contains the nutrients and water necessary for algae to grow. In addition to producing profitable goods, microalgae provide a low-cost, environmentally friendly way to clean advanced (Waste) water. The process of algal metabolism and cultivation is explored, specifically concerning the use of microalgae to remove metals. Additionally, biomass conversion techniques are investigated for converting algae into various forms of energy, such as fertilizers, biodiesel, bioethanol, and biohydrogen. Both organic and inorganic impurities can be effectively removed from water using the mixotrophic technique; the operating conditions can be regulated and photobioreactors are effective for cultivation. Algal biomass is economically significant for aquaculture, animal feed, health supplements, greenhouse gas reduction, and mitigation of global warming. The process of converting algal biomass into energy, biofuel, biodiesel, biogas, biohydrogen, and bioethanol is described in detail. The interaction between biotic and abiotic elements in wastewater treatment is also examined. Microalgae have been applied in agricultural and environmental contexts; in particular, they have been used to produce biomass for soil augmentation and absorb nutrients, highlighting their potential benefits to environmental stewardship and sustainability.

KEYWORDS: Microalgae, Wastewater, Cultivation, Harvesting, Algal biomass, Biodiesel, Biofuels.

INTRODUCTION

Large volumes of wastewater are generated by agriculture, urbanization, and industrialization. Eliminating wastewater that has not been treated beforehand causes major pollution problems. Algal bloom, nitrogen depletion, and significant biodiversity loss that leads to degraded freshwater environment are high challenges (Suganya and Kumar 2018; Vardhan et al. 2019). The diverse ecosystems support a variety of organisms that can be found in different types of water, including freshwater, brackish water, marine water, and even wastewater. These species include phytoplankton, such as microalgae, whose metabolic activity and structure differ significantly from higher plant microalgae. As wastewater generation continues to increase, the quality of our water resources is declining. However, the ability of microalgae to absorb nutrients from wastewater and convert them into biomass has sparked interest in using them for biofuel production. (Salama et al. (2017). Algal biofilm systems have proven to be highly beneficial in wastewater treatment. This is due to their efficient and uncomplicated method of absorbing nitrogen and phosphorus, followed by a reliable process to separate algae biomass from most wastewater (Miranda et al. (2017). Uncontrolled toxins are discharged into the environment as a result of population increase. This is because strict laws have been implemented regulating the required treatment of wastewater before its release into the environment, along with the development of a range of treatment techniques, as public concern over the preservation of natural water resources has grown (Derakhshan et al., 2017a, 2017b; Kumar et al., 2015). This paper briefly describes the existing techniques that have led to flotation lately emerging as a viable alternative. Humans can accumulate heavy metals across food systems and present health hazards to people. Even in small quantities, heavy metal ions are harmful to living things. Zinc exposure can cause various problems, including lack of appetite and excessive muscle contraction (Anitha et al. 2015; Monteiro et al. 2011b; Saravanan et al. 2018).

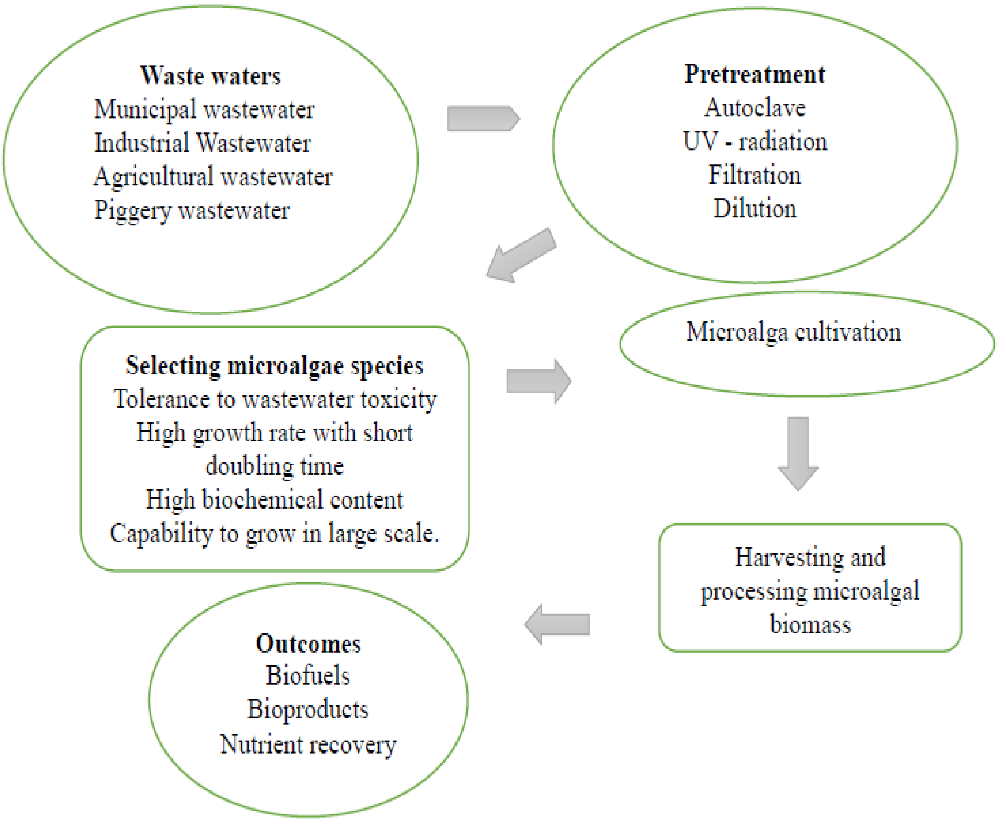

Fig. 1: Culturing Microalgae and Production of biofuel generation by wastewater treatment Adapted from (Salama et al. (2017).

1. Types of wastewater

1.1 Municipal wastewater

The main component of municipal wastewater is home water consumption. Therefore, readily degradable organic debris is the primary cause of their pollution. Nevertheless, several POPs are also found at microconcentrations or quantities smaller than milliliters per liter. Chemicals that fall into this concentration range are sometimes called micropollutants. Most of these micropollutants include hormones, medications, plasticizers, flame retardants, surfactants, and insecticides (Martin et al. (2021). Primary wastewater treatment schemes used by most municipal wastewater management plants comprise three main components: (1) a screening chamber for the removal of large solids from wastewater, (2) grit chambers for the removal of grit, and (3) primary sedimentation tanks for the removal of the majority of the particles at the bottom of the tank. A digester plant receives the sludge from the settling tank for further processing and disposal of solid waste. After that, the leftover wastewater is sent to a secondary treatment facility, where a trickling filter is used to further filter it (Salama et al. (2017).

1.2 Agricultural wastewater

The increasing global population generates more wastewater from cities and increases the demand for food production. A person needs between 2000 and 5000 L of drinking water to generate their daily food needs, according to the "Proceedings of the UN-Water project in Safe Use of Wastewater in Agriculture." Not only does the agriculture industry utilize the most drinking water, it also produces the most effluent (Mateo-Sagasta et al., 2013).

Other substances that may be present in agricultural wastewater include insecticides, herbicides, antibiotics, and other medications used for animals. The water goes through regular wastewater treatment, but the manure that comes with the wastewater is frequently used as fertilizer (Martin et al. (2021).

1.3 Industrial wastewater

There are many different types of industrial wastewater. The paper, cotton, and plywood sectors have exceptionally high water pollution and consumption rates. According to the C&A foundation, the water needed for its textile supply chain annually ranges from 5.7 to 9.7 billion m3 (Franke & Mathews, 2013). A precise assessment of the total amount of water consumed is nearly tricky due to the absence of reliable statistics regarding water consumption of the paper industry; nonetheless, the estimated water footprint of an A4 sheet of paper was between 13 and 20 L (Hoekstra, 2015).

These wastewaters often have more significant quantities of various carbon sources, but significantly lower levels of phosphorus and nitrogen. The plywood business is one of the most critical contributors to water pollution, even if its impact is less than that of the other two instances. High concentrations of particles, organic matter and nitrogen, together with hazardous substances such as phenol and heavy metals such as copper, cadmium, or lead, are the characteristics of wastewater from this business (Heng et al., 2004; Mukherjee et al., 2007; Muoz et al., 2006; Prasad et al., 2019).

1.4 Pump wastewater

Piggery wastewater is one of the most contaminated agroindustrial wastes due to its high organic matter content, high chemical oxygen demand (COD) and BOD values, and high organic nitrogen concentration. Most of the time, pig farms treat their wastewater biologically by using anaerobic bacteria to lower the amount of nutrients. The use of wastewater as a complex culture medium for microalgae could support the dual purposes of waste reduction and biofuel production (Salama et al.,2017).

2. Microalgae

Microalgae are unicellular organisms that are often found in freshwater and marine environments. They are an essential component of aquatic food chains. Together, these little creatures constitute a significant biomass that affects the world's climate systems. Each species has developed unique adaptations to survive in various environmental settings, demonstrating resistance to severe weather, high salinity, low pH, and prolonged exposure to light (Phillipa et al., 2014).

Large-scale resource production has both beneficial and detrimental effects on the environment. Microalgae have been the subject of many research projects, including studies on their potential as biological resources, sources of industrial and household wastewater cleanup, and production of food and pharmaceuticals, as well as biofuels and fertilizers (Phillipa et al., 2014).

3. Microalgae cultivation

Research and investment is being made in the rapidly expanding field of microalgae cultivation for use in fuel, food, medicine and agriculture is being done. Although microalgae have much potential to improve the environment over current biofuel technology, there are still challenges to be solved in wastewater treatment, emissions control, changing land uses, and the responsible creation of genetically modified organisms (Phillipa et al.,2014).

3.1 Open-pond system

One crucial factor is the method used to cultivate microalgae biomass for energy. Nowadays, in industrial-scale systems, open ponds are typically used due to cost concerns. Simple designs, such as circular or racetrack-shaped ground tanks with a maximum depth of 0.5 m, are the defining feature of these ponds, which paddle agitators mechanically churn. Adding wastewater to the system allows you to increase cleaning efficiency and remove up to 35 g of BZT/m2 d, compared to the 5–10 g of BZT/m2 d achieved in conventional stabilization ponds. Despite these benefits, there is still a lack of global acceptance of these devices for wastewater treatment (Marcin et al.,2012).

Table 1: Advantages and disadvantages of the open pond system of cultivation Adapted from (Salama et al., 2017).

Advantages	Disadvantages
Low price Simple to use and maintain. Absorbs CO2 from the environment. Equalizes flow	Elevated risk of contamination Loss of area and water Hardly and develop more slowly

3.2 Photobioreactors

The utilization of closed systems, or "photobioreactors," presents an entirely new strategy for addressing the issue of algal biomass proliferation and culture. Until now, many different types of these systems have been produced, such as biocoil-type reactors, continuous or semicontinuous massive bag systems, horizontal tube photobioreactors, or slopes under any angle (Marcin et al.,2012).

Closed frameworks are used because microalgae are grown in controlled environments and have higher volume output, cost, lipid yield, and biomass than open frameworks (Kirubanandam et al.,2020). Limitation, including overheating, construction costs, and scale - up has been addressed in Table 2

Table 2: Adapted from (Kirubanandam et al., 2020).

Limitations	Overheating, Construction costs, Scale – up
Design Consideration	(a) Fast transfer of CO2 and O2 masses equals light distribution. (b) Promotion of various micro-algae species (c) Adhesive nature for quick sterilization, mechanical cleaning (d) Operation in high friction
Recent Designs	Tubular vertical photobioreactor, airlift photo bioreactors. Helical photobioreactors Horizontal tubular photobioreactor Photobioreactor bubble column Stirred photobioreactor tanks.

Table 3: Advantages and disadvantages of microalgae photobioreactors. Adapted from (Kirubanandam et al. (2020).

Advantages	Disadvantages
1. Elevated Productivity and control levels 2. No chance of contamination 3. Absorbs CO2 from the atmosphere and from the exhaust	1. Expensive 2. Vast infrastructure 3. High upkeep and observation

3.3 Immobilized cell activation system

The growth curves of the immobilized cells resembled those of the free-living cells, except for a one-day longer lag phase that may be linked to the heat stress the cells experienced during their inclusion in carrageenan. The rates at which free and trapped cells absorbed phosphorus and nitrogen were similar. Because the inclusion material is expensive, this type of system is not yet suitable for large-scale operation. More effort is needed to identify affordable, readily implementable inert support (Joel et al. (1992). A biofilm is made up of a microalgae cell that has been adhered to a particular natural surface employing efficient adsorption, immobilization, polymer traps, covalent junctions, confinement of liquid fluid emulsion, and semipermeable membrane capture (De-Bashan and Bashan (2010). Polymer matrix cell entrapment uses polymers such as carrageen and alginate, solid surface biofilm development, and cell adhesion, standard techniques for immobilizing microalgae (Christenson and Sims 2011; Hameed and Ebrahim 2007).

4. Microalgae harvesting

The removal of algae from its growing medium is known as "harvesting algae." The techniques for harvesting microalgae depend on the selected microalgae's physiognomies, the microalgal cell's size and density, the final product requirements, and whether the growth medium may be reused (Laamanen et al. (2016). In diluted culture broth, microalgae develop. In this way, microalgae require a first concentration phase before extracting value-added products or producing biofuels. Microalgae cultivation typically takes two sequential phases and has a concentration of 0.5–2.5 gL-1. In the second harvesting process, which concentrates biomass up to 200–250 mg L−1 and increases the concentration by a factor of ten (Cristina and Mercedes Ballesteros, 2012).

4.1 Flocculation

Flocculation is done by adding chemicals such as alkaline compounds, metallic salts, or polyelectrolytes. NaOH, KOH, Ca (OH) 2 or Mg (OH)2 are alkaline compounds that cause biomass aggregation (Cristina and Mercedes Ballesteros (2012). Finding a highly effective and economical flocculant has always been problematic in most research, as it plays a significant part in flocculation harvesting. These days, excessive doses and biomass contamination have led to decreased usage of traditional inorganic metal salts such as ferric and aluminum sulfate (Ibrahim et al.,2019).

4.2 Sedimentation

Harvesting efficiency was measured based on sedimentation performances with and without flocculant. A 500 ml volume containing cultivated microalgae was added to the separation funnel for sedimentation without flocculant. A beaker containing 5% (v/v) of 1 M alum (Al2(SO4)3) was filled with the equivalent quantity of farmed microalgae to facilitate sedimentation using flocculant. After using a magnetic stirrer for a minute, the mixture was moved into an 8-hour separation funnel. OD650 readings were recorded at the bottom of the sediment once every hour to calculate the harvesting efficiency (Azima et al.,2017).

5. Biomass

Biomass harvesting contributes between 15% and 20% of the total manufacturing cost. Recovery of algae cells is difficult due to their tiny size and low concentration in the culture medium. Because different algae species have different characteristics, such as form, size, and motility, which significantly impact how they settle, harvesting cannot be done with a single procedure (Raja et al.,2014).

Economic importance of algal biomass

5.1 Health supplements

More than 75% of the yearly production of microalgal biomass was used to produce powders, pills, capsules or pastilles in the health food industry during the last several decades. Unicellular green algae, Chlorella, and filamentous blue-green algae, Spirulina (a cyanobacterium), have been the two main species raised for this purpose (Raja et al.,2014).

5.2 Animal Feed and Aquaculture

In addition to giving zooplankton food, microalgae also aid in regulating and enhancing the quality of culture media. The addition of phytoplankton to rearing ponds significantly improves the survival, growth, and transformation index for a wide range of freshwater and marine animal species (Muller-Feuga et al. (2000). The biological substances that are expelled trigger many behavioral responses, such as the initial capture of prey, control over the bacterial population, enhancement of immunity, and probiotic benefits (Raja et al.,2014).

5.3 Greenhouse gas Reductions and Global warming

Carbon dioxide is a potent greenhouse gas linked to catastrophic global warming and burning fossil fuels contributes significantly to its emission. Microalgae aid in biomitigation by absorbing carbon dioxide and other flue gases. The resulting algae biomass is rich in carbon that has been trapped and has a wide range of possible uses. Essential products such as fertilizer, biofuel, and animal feed can utilize this biomass. Therefore, by converting collected carbon into valuable goods, microalgae provide a sustainable and multifunctional solution and a viable path to reduce greenhouse gas emissions (Raja et al., 2014).

6. Biodiesel

Excess methanol triglycerides are converted to biodiesel by transesterification reactions between glycerol and methyl esters of fatty acids. Catalysts such as NaOH or KOH are added at 1 hour, 30 minutes and 60 degrees Celsius under atmospheric pressure to speed up conversion and reduce response time (Aresta et al. 2005). Three generations of biodiesel can be produced from triglyceride sources. In the first, second, and third generations of biodiesel, edible, nonedible, and microalgae are combined. When algae develop and release the ignition fuel, 100% of the CO2 is absorbed by algal biodiesel, a carbohydrate fuel. Because of this, this fuel is seen as an appropriate and secure response to environmental changes (Najafi et al.,2011; Ziolkowska and Simon,2014).

Two categories of microalgae can be used as feedstock: freshwater and saltwater algae. Seawater microalgae are considered sustainable (Velasquez-Orta et al.,2013). Low quality biodiesel is due to the rising expenses associated with synergistic splitting, pyrolysis, or miniature emulsification. In this case, transesterification is the most popular method for turning oil into biodiesel. Transesterification converts safe unsaturated fats, triacylglycerols, or corrosive alkyl esters into dense microalgae lipids to lower the molecular weight of fats. Phosphoric acid, sulfonic acid, sulfuric acid, hydrochloric acid, sodium methoxide, potassium hydroxide, and sodium hydroxide are examples of acid catalysts used in transesterification. Heterogeneous inorganic catalysts, enzymes, and heterogeneous inorganic catalysts are examples of alkaline catalysts (Rawat et al.,2011),

6.1 Biofuel

Nitrogen oxides, carbohydrates, carbon monoxide, sulfur oxides, partially burnt hydrocarbons, trace chemicals, and particles are released during the combustion of aviation fuel. Due to the increased demand for travel, the petroleum business uses five million barrels of oil daily. The aviation sector must employ alternative fuels to reduce its carbon footprint and impact the atmospheric circulation that leads to ozone depletion and climate change. Because algae photosynthesis is intimately connected to their rich oil structure, algae biofuels from their feedstock are becoming more sustainable. The remarkable oil production of algae is diminished by cell structure separation due to their absorption of CO_2, which transforms into oxygen (Hallenbeck et al.,2016; Laamanen et al.,2016; Suganya et al.,2016).

6.2 Electricity

The microbial fuel cell (MFC) has proven to have enormous capacity to produce power (Zhou et al. 2012). It is an electrical device that uses biocatalysts to facilitate the direct and effective conversion of certain organic materials to bioelectricity through redox processes. The independent and anode-grade redox processes that are isolated by a membrane (Logan and Rabaey 2012; Mathuriya and Yakhmi 2014). The arrangement of the cathode and anode determines whether the bioreactor has two or one chamber. The value of MFCs is influenced by composition, wastewater, bioreactor size, electrode design, catholyte, and microbial products (Kondaveeti et al. 2017, 2018). Some algae cathode microbial fuel cells fed wastewater to recover nutrients. With a high cell voltage of 300 mV and an average dissolved oxygen of 19.5 mg/L, the cell voltage has dropped as the level of leachate has increased (Nguyen et al.,2017).

6.3 Biogas

Biogas production is a biochemical process that involves numerous required or optional anaerobic bacteria that work together in concert. Microorganisms are essential for the effectiveness of biogas generation (Deng et al. (2020). Depending on the type of raw material used, biogas can have a different composition. In a functioning digester, it can comprise anywhere between 25% and 50% CO_2 and 50% to 75% CH_4, along with additional elements such as water vapor (H_2O), hydrogen sulfide (H_2S) and ammonia (NH_3) (Andrade et al.,2020).

6.4 Biohydrogen

A natural and ephemeral byproduct of many biochemical events of microbial origin, "biohydrogen" is described as H_2 gas produced by biological machinery or thermochemically treating biomass. Because biomass is used as a substrate or raw material in the thermochemical production of H_2, the gas is also known as a biohydrogen. However, several biological pathways can be used to produce bio-hydrogen, including enzymatic, photobiological, anaerobic/fermentation, and electrogenic processes (Mohan and Pandey,2013).

Hydrogen represents an endless, cost-effective, and environmentally friendly source of pure energy. With current technical advances, processing techniques, and expanded research on hydrogen technology, a sustainable bioenergy source might soon be available. In the 1970s, the generation of hydrogen from microalgae was attributed to metabolic, genetic, and enzyme problems. Biohydrogen production is a photobiological process that uses sunlight and water (Cheng and Chang, 2011).

6.5 Bioethanol

The most commonly utilized liquid biofuel is ethanol. Fermenting from sugars, starches, or cellulosic biomass is an alcohol. As a result of the high pretreatment costs associated with starches and cellulosic biomass, sugarcane and beet are the primary sources of ethanol used in commerce. In most cases, it is utilized as a renewable fuel source and in the manufacture of alcoholic drinks, medications, and cosmetics (Demirbas,2005).

The pretreatment of biomass, hydrolysis, fermentation, and product recovery are some steps in the process that goes into the production of bioethanol. Biomass pretreatment is one of the most crucial and costly steps. Pretreatment is required to improve substrate digestibility by decreasing biomass crystallinity and increasing its surface area (Harun et al.,2011; Sarkar et al.,2012).

7. Abiotic and biotic variables affecting wastewater treatment using microalgae

7.1 Bacteria

Numerous studies on wastewater treatment have been conducted using a single microalgal species or a group of related species. In actuality, additional microorganisms (such as bacteria and fungi) in a microalgal wastewater treatment system cannot be prevented due to the large quantities of water that must be handled, making prior water sterilization impractical. Under these circumstances, operational and environmental factors and the composition of the wastewater that is treated often influence the dynamics of the community structure (Posadas et al., 2014; Ferrero et al., 2012).

Bacteria are required for wastewater treatment and can even help micro-algae. By providing CO2 through their heterotrophic metabolism of organic matter and mineralizing it into inorganic compounds such as NH4 + and PO4-3 that the microalgae can directly consume, bacteria can help in the photoautotrophic growth of microalgae (Bordel et al., 2009; de Godos et al., 2010).

7.2 Industrial contaminants

Microalgae have shown significant promise in removing heavy metals and pharmaceutical contaminants, among other industrial contaminants. According to a study on the effectiveness of HRAP for removing pharmaceuticals from urban wastewater, some environmentally dangerous pharmaceuticals, like diclofenac and antibiotics, were more effectively removed by HRAP. However, the most widely used analgesics and anti-inflammatory drugs, such as ibuprofen and paracetamol, were marginally more effectively removed in traditional WWTP (Villar-Navarro et al., 2020).

7.3 P^H

Abiotic processes through which bacteria and microalgae negatively impact one another have been documented in several studies; for instance, bacterial activity may suffer from increases in pH and dissolved O2 concentration seen in microalgae cultures (Schumacher et al.,2003), Ansa et al.,2011). Other studies have demonstrated a substantial relationship between the number of heterotrophic bacteria and pH, showing an increase in the "inactivation" of bacteria with increasing pH (Ansa et al., 2011; Awuah et al., 2001; Ansa et al., 2012).

7.4 Temperature and Light

Exogenous microalgae, added to wastewater, may compete with the autochthonous microbial population for resources when nutrients (such as N and P) become scarce (Lee et al., 2013a, 2013b; Grover, 2000). Therefore, establishing an environment that encourages the growth of microalgae over that of bacteria and fungi is therefore crucial. Light and temperature are essential factors in this situation. For microalgal activity to occur usually, light availability is essential. Light energy drives the evolution of O2 and produces ATP and reducing agents, which are needed to fix CO2 into organic carbon (Falkowski & Raven, 2007; Williams and Laurens, 2010).

8. Algal for removal of heavy metals

Heavy metal is a dangerous or toxic metal component with medium density and low concentration. According to the ecological classification, any element that does not cause organic injury or substantial environmental damage is considered a heavy metal. Heavy metals such as Cu, Ni, Mn, Co and Zn are essential micronutrients for plant growth, although their biological function is uncertain and potentially dangerous (Herrera-Estrella and Guevara-Garca (2009); these heavy metals are divided into three groups: radionuclides (U, Ra, Am, and Th), hazardous metals (Zn, Ni, Ag, Cu, Cr, As, Sn, Co, and Pb), and valuable metals (Au, Pd, Pt and Ru) (Wang and Chen (2009), Urbanization, population expansion, and industry are setting the stage for a global interest in heavy metal improvement in many biological systems. The historical use of heavy metals is covered in several publications from many industries, and the disposal of wastewater and agricultural practices is a significant worldwide issue.

To form microalgae and extract nutrients for the cycle, these microbes generate CO2 and other additives required for photosynthesis (Park et al. 2011). Initially, algal ponds were designed to prevent the eutrophication of secondary effluents by treating them before water was released (Oswald and Golueke, 1960). Live cell bioaccumulation and non-living biosorption are two categories into which the recovery phenomena may be divided. Continuous self-reloading frames are allowed to run for an extended period of time in the earlier technique, which applies the idea of waste detoxification. If their metal toxicity has no effect on cell proliferation, Heavy metal ions will be concentrated to a comparable or greater extent in subsequent systems' dead cells that have been chemically treated, acidic, dried, or heated to death (frameworks (Kirubanandam et al.,2020).

9. Environmental and Agricultural applications

The capacity of microalgae to extract more than 90% of nutrients and a certain amount of hazardous compounds and heavy metals from industrial wastewater may be further enhanced by the use of growth stimulators or through the development of growth. Furthermore, microalgae, mainly cyanobacteria, are considered a viable source of exopolysaccharide and biomass production on a large scale to disperse inoculum in the field in an environmentally responsible and efficient manner from the standpoint of improving soil environments (Tiwari et al. 2019). The biomass of these microbes has been shown to include higher concentrations of lipids, proteins, and pigments. They also recycle water, which has uses in bioenergy (Zhu et al. 2019) and agriculture (Castro et al. 2020).

CONCLUSION

Information on microalgae encompasses a wide range of subjects, highlighting their culture, uses in wastewater treatment, economic importance, and capacity to yield valuable goods. The review of different types of wastewater, such as industrial, agricultural, and municipal wastewater, highlights microalgae's vital role of microalgae in mitigating environmental problems by acting as efficient agents in removing contaminants. Open-pond systems, photobioreactors, and immobilized cell activation systems are some of the culture techniques that demonstrate the adaptability and developing technology. Every cultivation technique has benefits and drawbacks, taking into account variables such as cost, effectiveness, and scalability.

An essential part of the manufacturing process is the harvesting of microalgae; several techniques are covered, including flocculation and sedimentation. Algal biomass has several uses, from producing biofuel power and reducing greenhouse gas emissions to serving as feed and health supplements. This highlights the material and economic significance of algal biomass. The intricate relationships between bacteria, industrial pollutants, pH, temperature, and light are highlighted in the section on abiotic and biotic parameters that impact wastewater treatment using microalgae. The article emphasizes the potential of microalgae in agricultural and environmental applications, such as the extraction of nutrients from industrial effluent and the large-scale production of biomass to improve soil.

REFERENCES

1. Ana F. Miranda, Narasimhan Ramkumar, Constandino Andriotis, Thorben Höltkemeier, Aneela Yasmin, Simone Rochfort, Donald Wlodkowic, Paul Morrison, Felicity Roddick, German Spangenberg, Banwari Lal, Sanjukta Subudhi and Aidyn Mouradov Applications of microalgal bioflms for wastewater treatment and bioenergy production, 2017. DOI 10.1186/s13068-017-0798-9
2. Andrade DS, Gavilanes FZ, Silva HR, Henrique Leite Castro G, Telles TS Sustainable bioenergy production. Elsevier, London, 2020a; 363–391. https://doi.org/10.1016/b978-0-12-819597-0.00019-2
3. Anitha T, Senthil Kumar P, Sathish Kumar K Binding of Zn (II) ions to chitosan–PVA blend in aqueous environment: adsorption kinetics and equilibrium studies. Environ Prog Sustain Energy, 2015; 34(1): 15–22. https ://doi.org/10.1002/ep.11943
4. Ansa, E.D.O., Lubberding, H.J., Ampofo, J.A., Gijzen, H.J., The role of algae in the removal of Escherichia, 2011.
5. Ansa, E.D.O., Lubberding, H.J., Gijzen, H.J., The effect of algal biomass on the removal of faecal coliform from domestic wastewater. Appl Water Sci, 2012; 2: 87–94.
6. Aresta M, Dibenedetto A, Carone M, Colonna T, Fragale C Production of biodiesel from macroalgae by supercritical CO2 extraction and thermochemical liquefaction. Environ Chem Lett, 2005; 3(3): 136–139. https ://doi.org/10.1007/s1031 1-005-0020-3

7. Awuah, E., Anohene, F., Asante, K., Lubberding, H., Gijzen, H., Environmental conditions and pathogen removal in macrophyte- and algal-based domestic wastewater treatment systems. Water Sci. Technol, 2001; 44: 11–18.
8. Azima Syafaini Japar1, Nur Mutmainnah Azis1, Mohd. Sobri Takriff2, Nazlina Haiza Mohd Yasin2 Application of Different Techniques to Harvest Microalgae, 2017. https://tost.unise.org/pdfs/vol4/no2/4x2x98x108.pdf
9. Bordel, S., Guieysse, B., Muñoz, R., Mechanistic model for the reclamation of indus trial wastewaters using algal-bacterial photobioreactors. Environ. Sci. Technol, 2009; 43: 3200–3207.
10. Borowitzka MA, Borowitzka LJ Dunaliella. Microalgal biotechnology, Cambridge University Press, New York, USA, 1988.
11. Castro JDS, Calijuri ML, Mattiello EM, Ribeiro VJ, Assemany PP Algal biomass from wastewater: soil phosphorus bioavailability and plants productivity. Sci Total Environ, 2020; 711: 135088. https://doi.org/10.1016/j.scitotenv.2019.135088
12. Cristina and & Mercedes Ballesteros Microalgae autoflocculation: an alternative to high-energy consuming harvesting methods, 2012. DOI 10.1007/s10811-012-9957-3.
13. Cheng C-L, Chang J-S Hydrolysis of lignocellulosic feedstock by novel cellulases originating from Pseudomonas sp. CL3 for fermentative hydrogen production. Bioresour Technol, 2011; 102(18): 8628–8634. https ://doi.org/10.1016/j.biort ech.2011.03.053.
14. Derakhshan, Z., Ehrampoush, M.H., Faramarzian, M., Ghaneian, M.T., Mahvi, A.H., Waste tire chunks as a novel packing media in a fixed-bed sequence batch reactors: volumetric removal modeling. Desalin. Water Treat, 2017; 64: 40-47.
15. Derakhshan, Z., Ghaneian, M.T., Mahvi, A.H., Conti, G.O., Faramarzian, M., Dehghani, M., Ferrante, M., A new recycling technique for the waste tires reuse. Environ. Res, 2017b; 158: 462-469.
16. Deng L, Liu Y, Wang W Biogas technology, 2020. https://doi.org/10.1007/978-981-15-4940-3
17. DemirbaS A Bioethanol from cellulosic materials: a renewable motor fuel from biomass. Energy Sources, 2005; 27: 327–337. https://doi.org/10.1080/00908310390266643
18. De Godos, I., Vargas, V.A., Blanco, S., González, M.C.G., Soto, R., García-Encina, P.A., Becares, E., Muñoz, R., A comparative evaluation of microalgae for the degradation piggery wastewater under photosynthetic oxygenation. Bioresour. Technol, 2010; 101: 5150–5158.

19. El-Sayed Salama, Mayur B. Kurade, Reda A.I. Abou-Shanab, Marwa M. Ei-Dalatony, Il-Seung Yang, Booki Min, Byong- Hun Jeon Recent progress in microalgae biomass production coupled with wastewater treatment for biofuel generation, 2017; 79(1189-1211).
20. Falkowski, P.G., Raven, J.A., Aquatic Photosynthesis.Princeton University Press, New Jersey, USA, 2007; 2.
21. Grover, J.P., Resource competition and community structure in aquatic microorganisms: experimental studies of algae and bacteria along a gradient of organic carbon to inorganic phosphorus supply. J. Plankton Res, 2000; 22: 1591–1610.
22. Harun R, Jason WSY, Cherrington T, Danquah MK Exploring alkaline pretreatment of microalgal biomass for bioethanol production. Appl Energy, 2011; 88: 3464–3467. https://doi.org/10.1016/j.apenergy.2010.10.048.
23. Hallenbeck P, Grogger M, Mraz M, Veverka D Solar biofuels production with microalgae. Appl Energy, 2016; 179: 136–145. https :// doi.org/10.1016/j.apene rgy.2016.06.024
24. Herrera-Estrella LR, Guevara-García AA Heavy metal adaptation. eLS, 2009. https ://doi.org/10.1038/npg.els.00013 18
25. Ibrahim A. Matter 1,2, Vu Khac Hoang Bui 3, Mikyoung Jung 1, Jung Yoon Seo 4, Young-Eun Kim 1, Young-Chul Lee 3, and You-Kwan Oh 1, Flocculation Harvesting Techniques for Microalgae, 2019. A Review file:///C:/Users/gotir/Downloads/applsci-09-03069-v2.pdf
26. Joel de la Noue, Gilles Laliberte & Daniel Proulx (1992) Algae and wastewater, 1992; 247-254.
27. Kumar, K.S., Dahms, H 1 - U ., Won, E.-J., Lee, J.-S., Shin, K.-H.. Microalgae-A promising tool for heavy metal remediation. Ecotoxicol. Environ. Saf, 2015; 113: 329-352.
28. Laamanen CA, Ross GM, Scott JA Flotation harvesting of microalgae. Renew Sustain Energy Rev, 2016; 58: 75–86. https ://doi. org/10.1016/j.rser.2015.12.293
29. Lee, J., Lee, J., Lee, T.K., Woo, S.G., Baek, G.S., Park, J., In-depth characterization of wastewater bacterial community in response to algal growth using pyrosequencing. J. Microbiol. Biotechnol, 2013a; 23: 1472–1477.
30. Lee, J., Cho, D.-H., Ramanan, R., Kim, B.-H., Oh, H.-M., Kim, H.-S., Microalgae associated bacteria play a key role in the flocculation of Chlorella vulgaris. Bioresour Technol, 2013; 131: 195–201.

31. Logan BE, Rabaey K Conversion of wastes into bioelectricity and chemicals by using microbial electrochemical technologies. Science, 2012; 337(6095): 686–690. https ://doi.org/10.1126/science.12174 12
32. Lorenz RT, Cysewski GR Commercial potential for Haematococcus microalgae as a natural source of astaxanthin. Trends Biotechnol, 2000; 18: 160-167.
33. Marcin Debowski, Marcin Zielinski, Mirostaw Krzemieniewski, Magda Dudek, Anna Grala Microalgae cultivation methods, 2012; 27(20: 151-164. https://www.uwm.edu.pl/polish-journal/sites/default/files/issues/articles/debowski_et_al._2012.pdf
34. Martin Plohn, Olivia Spain, Sema Sirin, Mario Silva, Carlos Escudero- Onate, Laura Ferrando- Climent, Yagut Allahverdiyeva, Christiane Funk Wastewater treatment by microalgae, 2021. https://doi.org/10.1111/ppl.13427.
35. Mateo-Sagasta, J., Medlicott, K., Qadir, M., Raschid-Sally, L., Drechsel, P., *Proceedings of the UN-water project on the safe use of wastewater in agriculture*. Bonn: United Nations University. UN-Water Decade Programme on Capacity Development (UNW-DPC), 2013.
36. Monteiro CM, Castro PM, Malcata FX Capacity of simultaneous removal of zinc and cadmium from contaminated media, by two microalgae isolated from a polluted site. Environ Chem Lett, 2011b; 9(4): 511–517. https ://doi.org/10.1007/s1031 1-011-0311-9
37. Mukherjee, S., Kumar, S., Misra, A.K. & Fan, M. Removal of phenols from water environment by activated carbon, bagasse ash and wood charcoal. *Chemical Engineering Journal*, 2007; 129: 133–142.
38. Munoz, R., Alvarez, M.T., Munoz, A., Terrazas, E., Guieysse, B. & Mattiasson, B. Sequential removal of heavy metals ions and organic pollutants using an algal-bacterial consortium. *Chemosphere*, 2006; 63, 903–911. https://doi.org/10.1016/j.chemosphere.2005.09.062.
39. Mohan SV, Pandey A Biohydrogen production: an introduction. Biohydrogen, 2013; 5: 1–24. https://doi.org/10.1016/B978-0-444-59555-3.00001-5
40. Muller-Feuga A The role of microalgae in aquaculture: situation and trends. J Appl Phycol, 2000; 12: 527-534.
41. Mathuriya AS, Yakhmi J Microbial fuel cells to recover heavy metals. Environ Chem Lett, 2014; 12(4): 483–494. https ://doi. org/10.1007/s1031 1-014-0474-2

42. Najafi G, Ghobadian B, Yusaf TF Algae as a sustainable energy source for biofuel production in Iran: a case study. Renew Sustain Energy Rev, 2011; 15(8): 3870–3876. https ://doi.org/10.1016/j. rser.2011.07.010
43. Nguyen HT, Kakarla R, Min B Algae cathode microbial fuel cells for electricity generation and nutrient removal from landfill leachate wastewater. Int J Hydrogen Energy, 2017; 42(49): 29433– 29442. https ://doi.org/10.1016/j.ijhyd ene.2017.10.011
44. Oswald WJ, Golueke CG Biological transformation of solar energy. Adv Appl Microbiol, 1960; 2: 223–262. https ://doi. org/10.1016/S0065 -2164(08)70127 -8
45. Park J, Craggs R, Shilton A Wastewater treatment high rate algal ponds for biofuel production. Biores Technol, 2011; 102(1): 35– 42. https ://doi.org/10.1016/j.biort ech.2010.06.158
46. Philippa k. Usher, Andrew B. Ross, Miller Alonso Camargo-Valero, Alison S. Tomlin & William F. Gale An overview of the potential environment impacts of large-scale microalgae cultivation, 2014. https://doi.org/10.1080/17597269.2014.913925
47. Prasad, H., Lohchab, R. K., Singh, B., Nain, A. & Kumari, M. Lime treatment of wastewater in a plywood industry to achieve the zero liquid discharge. *Journal of Cleaner Production*, 2019; 240: 118176.
48. Posadas, E., García-Encina, P.A., Domínguez, A., Díaz, I., Becares, E., Blanco, S., Muñoz, R., Enclosed tubular and open algal–bacterial biofilm photobioreactors for carbon and nutrient removal from domestic wastewater. Ecol. Eng, 2014; 67: 156–164.
49. Raja R, Shanmugam H, Ganesan V, Carvalho IS Biomass from Microalgae: An Overview. Oceanography, 2014; 2: 118. doi:10.4172/2332- 2632.1000118
50. Rawat I, Kumar RR, Mutanda T, Bux F Dual role of microalgae: phycoremediation of domestic wastewater and biomass production for sustainable biofuels production. Appl Energy, 2011; 88(10): 3411–3424. https ://doi.org/10.1016/j.apene rgy.2010.11.025
51. Sarkar N, Ghosh SK, Bannerjee S, Aikat K Bioethanol production from agricultural wastes: an overview. Renew Energy, 2012; 37: 19–27. https://doi.org/10.1016/j.renene.2011.06.045
52. Schumacher, G., Blume, T., Sekoulov, I., Bacteria reduction and nutrient removal in small wastewater treatment plants by an algal biofilm. Water Sci. Technol, 2003; 47: 195–202.
53. Suganya T, Varman M, Masjuki H, Renganathan S Macroalgae and microalgae as a potential source for commercial applications along with biofuels production: a biorefinery approach. Renew Sustain Energy Rev, 2016; 55: 909–941. https ://doi.org/10.1016/j. rser.2015.11.026

54. Tiwari ON, Bhunia B, Mondal A, Gopikrishna K, Indrama T System metabolic engineering of exopolysaccharide-producing cyanobacteria in soil rehabilitation by inducing the formation of biological soil crusts: a review. J Clean Prod, 2019; 211: 70–82. https://doi.org/10.1016/j.jclepro.2018.11.188
55. Villar-Navarro, E., Baena-Nogueras, R.M., et al., Removal of pharmaceuticals in urban wastewater: highrate algae pond (HRAP) based technologies as an alternative to activated sludge based processes. Water Res, 2020; 139: 19–29.
56. Velasquez-Orta S, Lee J, Harvey A Evaluation of FAME production from wet marine and freshwater microalgae by in situ transesterification. Biochem Eng J, 2013; 76: 83–89. https ://doi. org/10.1016/j.bej.2013.04.003
57. Williams, P.J.B., Laurens, L.M.L., Microalgae as biodiesel and biomass feedstocks: review & analysis of the biochemistry, energetics & economics. Energy Environ. Sci, 2010; 3: 554.
58. Wang L, Addy M, Lu Q, Cobb K, Chen P, Chen X, Liu Y, Wang H, Ruan R Cultivation of Chlorella vulgaris in sludge extracts: nutrient removal and algal utilization. Biores Technol, 2019b; 280: 505–510. https ://doi.org/10.1016/j.biort ech.2019.02.017
59. Ziolkowska JR, Simon L Recent developments and prospects for algae-based fuels in the US. Renew Sustain Energy Rev, 2014; 29: 847– 853. https ://doi.org/10.1016/j.rser.2013.09.021
60. Zhu S, Feng S, Xu Z, Qin L, Shang C et al Cultivation of *Chlorella vulgaris* on unsterilized dairy-derived liquid digestate for simultaneous biofuels feedstock production and pollutant removal. Bioresour Technol, 2019; 285: 121353. https://doi.org/10.1016/j.biortech.2019.121353.