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INNOVATIONS IN MICROALGAE-BASED WASTEWATER REMEDIATION, WHICH SIMULTANEOUSLY RECOVERS VALUE-ADDED PRODUCTS FROM INDUSTRIAL AND NON-INDUSTRIAL WASTEWATER: A REVIEW

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ABSTRACT

It has been demonstrated that microalgae can be utilized to treat industrial, municipal and agricultural wastewater as well as turn nutrients into biomass. Understanding how microalgae extract nutrients and contaminants from wastewater is essential to increasing the efficiency of wastewater treatment and the productivity of algal biomass. Large-scale microalgae production now takes place in enclosed photo bioreactors and open ponds, and numerous harvesting techniques are being developed to capture microalgae as much as possible at a reasonable cost. Because microalgae can manufacture many different kinds of goods with added value and are abundant in pigments, proteins, lipids, crabs, vitamins and antioxidants, this biotechnology is more affordable. Microalgae-based wastewater treatment is a cost-effective and ecologically beneficial solution to manage wastewater, because the post-treatment microalgae biomass is also a significant source of high-value products. The fields of exopolysaccharides, biofuel generation, bioplastics, and water filtration all have a lot of potential in the study of Phycology. It is imperative to handle sewage waste sustainably, use microalgal assistance to fully utilize the nutrients it contains and support a biorefinery strategy.

***Keywords* :** Microalgae, Wastewater treatment, Biorefinery, Bioplastics, Biofuel generation.

Introduction

The discharge of wastewater needs adequate treatment because of the existence of both organic and inorganic diseases, in addition to microorganisms that pollute water bodies and pose a threat to public health and safety Obotey *et al.*, 2020). Water demand has surged and there is a water deficit as a result of global economic and sociological development. According to reports, if current water use patterns continue, There may be a 40% worldwide water deficit by 2030 Sun *et al.* (2016). Microalgae-based systems are better at bioremediating wastewater (WW) and can 45–65% of BOD & COD ought to get eradicated Geremia *et al.* (2021). It's not a novel concept to utilize microalgae to treat wastewater, and a number of researchers have created methods to take advantage of the algae's ability to grow quickly and remove nutrients. Traditional wastewater treatment plants (WWTPs) are currently facing challenges before they can release and reuse wastewater into the environment due to severe pollution limits set by circular economy concepts. Thus, a fit-for-purpose technique might be employed to reduce the cost of wastewater recycling while enabling selective water reuse and water savings. Mathews & Tan (2016). Although other nutrient stripping events, such as ammonia volatilisation and phosphorus precipitation as a result of the high pH generated by the algae, occur, the predominant driver of nutrient removal is the assimilation of nutrients as the algae expand Hammouda *et al.*, 1995). Our utilization of natural resources is inevitably challenged by current global environmental difficulties. Providing clean water to the world's population is increasingly becoming a worldwide issue. A wide range of organic and inorganic toxins present in municipal, industrial, and agricultural streams endanger our health and nutrition.These contaminants include heavy metals, micro plastics, and high nutrient loads (Nagarajan *et al.*, 2019).According to recent studies, microalgae can also be used to remove pesticides and pharmaceutical chemicals from wastewater produced by industries and farms. This is in addition to their ability to remove nutrients from wastewater generated by WWTPs (Wang, Liu *et al.*, 2017). Algal-based systems are among the cutting-edge WWT technologies that show promise as sustainable and environmentally friendly substitutes for the status quo. Algae's capacity for metabolism allows them to develop in wastewaters by consuming the organic and nutritional contents. Algal processes can be powered by energy from sunlight or the wastewater itself, in contrast to the present energy-intensive systems. Algal systems for low-cost, energy-efficient WWT were first engineered by Oswald and colleagues Oswald (2003). Although microalgae can absorb nutrients; they can be used for tertiary wastewater treatment. In addition to causing phosphorus precipitation and ammonia stripping to the air, the pH increase caused by the expanding algae may also sterilize the wastewater. Because domestic wastewater includes high concentrations of all essential elements, it is perfect for algae growth. The three most crucial operational elements for effective microalgae-based wastewater treatment are hydraulic retention time, turbulence, and depth (Larsdotter *et al.*, 2007). The focus of current research has been on growing microalgae-bacteria granules, which restricts their use to wastewater treatment. Because it doesn't need to be further purified and has more possible uses, the cultivation of microalgae granules without bacterium has more promise (Kabir *et al.*, 2024). A collection of reported experiences with using microalgae to clean wastewater may be found in this chapter. This chapter's objective is to give readers a thorough grasp of the symbiotic interconnections that are established between microalgae and other microbes in wastewater treatments in addition to the method by which different pollutants and toxins are removed from wastewater. The output of microalgae cultivation is influenced by the species chosen for wastewater cultivation, the kind of wastewater, the method used, the climate (temperature and sunshine, for example), and the availability of CO_2. By using this method, it is feasible to produce biomass from microalgae while also bio remediating wastewater (mostly by removing elements like nitrogen and phosphorus). It appears from this that wastewater has all the essential nutrients needed to cultivate and produce algal biomass, which is suitable for a variety of purposes, including:

(i) Producing energy for biofuels such as biodiesel, biogas, and biohydrogen.

(ii) High-value biomolecules derived from microalgae can be used in pharmaceuticals, food products, and supplements.

(iii) bioplastics;

(iv) Chemicals: fertilisers and charcoal (Geremia *et al.*, 2021).

Treatment of algal generated wastewater

Microalgae treatment for wastewater treatment is not only a viable and affordable way to bio-fix CO_2, but it is also a renewable supply of biomass (Almomani *et al.*, 2019).If wastewater is continuously disposed of without sufficient treatment, major pollution issues may arise. A significant issue arising from the ongoing release of wastewater into aquatic environments is the phenomena known as eutrophication, which is the increase in nutrient levels in water resources, mostly nitrogen and phosphorus. Freshwater ecosystems are completely degraded as a result of this phenomenon, which also causes algal blooms, the expansion of aquatic plants, oxygen depletion, and the extinction of important species Renuka *et al*., & Ruiz *et al.*, 2013). Micro-algae, such as cyanobacteria and eukaryotic algae, have proven to be a viable and environmentally beneficial substitute for the energy-intensive, traditional biological treatment methods still in use today Singh *et al.*, 2015 & Oswald (2003). Plenty of studies have demonstrated that algal formation can promote nitrogen removal in wastewater, despite the fact that it is difficult to compare the outcomes of algal growth in wastewater treatment Chawla *et al.* (2020).

Innovations in microalgae-based wastewater remediation

Innovations in Membrane and Reactor Design for MPBR

A novel method for treating wastewater using algae is the membrane photobioreactor (MPBR) system (Goh *et al*., 2022). MPBRs can significantly reduce the amount of nutrients in the wastewater culture medium and produce highly concentrated biomass.

However, integrating biological and physical therapy units presents new operational challenges for MPBR systems, which complicates their deployment in several ways. Luo (2017) and associates. The efficiency of wastewater treatment and nutrient recovery has been enhanced by the integration of many approaches in microalgae-based MPBRs.

The main goal of membrane research is usually to decrease membrane fouling in addition to enhancing MPBR performance. It has been demonstrated that the MPBR system can achieve a high permeate flow recovery of >80% with periodic membrane backwashing (Shekhar *et al*., 2017). Furthermore, the propensity of membrane fouling in MPBRs has been reduced by the creation of a special reactor and an antifouling membrane.

The MPBR used in situ mechanical membrane cleaning to lower chemical agent consumption and operational fouling. A reciprocal MPBR with a spongy blade was created in order to eliminate the cake layer that builds up on the membrane surface (Azizi *et al*., 2021). To assess the transmembrane pressure (TMP) of the MPBR membrane and activate the spongy blade for cleaning, a programmed PLC system was created. Without the need for chemical cleaning or washing, the mechanical cleaning was able to lower the overall hydraulic resistance by up to 83%.

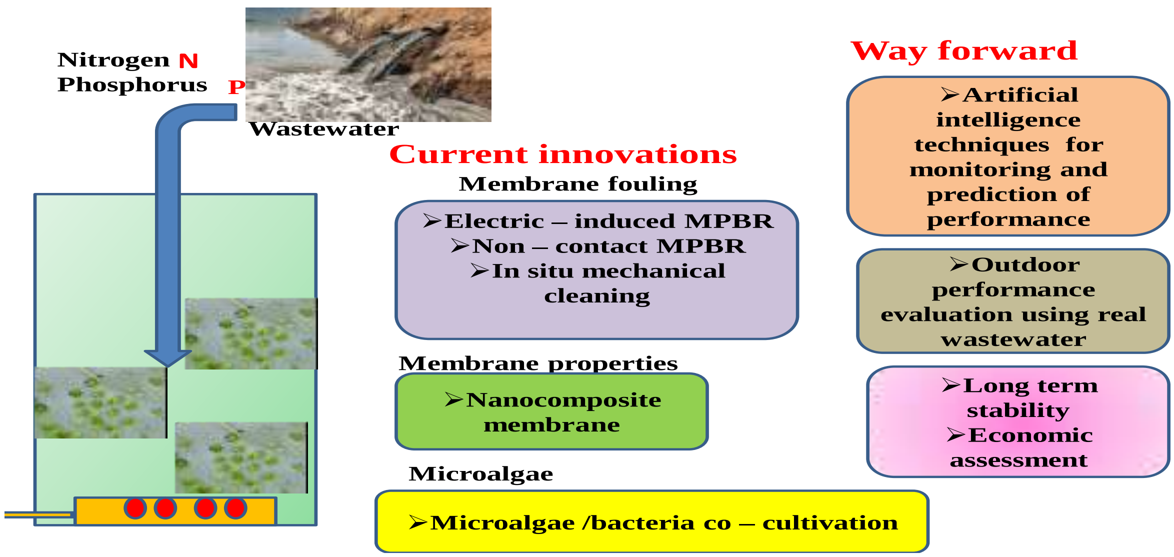

Fig. 1 : demonstrating the recent breakthrough in microalgae-based MPBRs

Bioprocessing of Wastewater: Microalgae are used in wastewater treatment plants to boost biomass and treat eutrophication in end users, in addition to acting as biological indicators. They are capable of breaking down nitrogen, phosphorus, heavy metals, and organic substances found in wastewater treatment facilities. Zabochnicka studied ammonium nitrogen from industrial wastewater using immobilised microalgae, attaining up to 60% expulsion proficiency (*C. vulgaris*) and 42% (*S. armatus*).

Open culture systems known as high-performance tanks (HRAPs) efficiently and effectively treat wastewater. Additionally, they employ immobilised cell methods. The biomass produced by these systems can be used to produce animal feed, biofuels, and other products, but it cannot be consumed by humans. It is noteworthy that 99% of the phosphates were eliminated from the effluents of an anaerobic digester of a starch industry plant that used Spirulina platensis, cultivated in HRAP, and that pigments from textile industry effluents were extracted from microalgae Chlorella vulgaris by immobilisation in alginate beds.

For many years, species of the genus *Chlorella*, including Pseudo *kirchneriella subcapitata*, *Dunailella tertiolecta*, and *Isochrysis galbana*, have been employed as biological markers. The tropical organisms *Ankistrodemsus* convolutes, *Chlorella vulgaris*, and *Scenedesmus quadricauda* are frequently employed in the evaluation of the phosphorus and nitrogen content in freshwater zones (Rizwan *et al*., 2018). Open systems and bioreactors are the primary methods used in large-scale research to process and extract nutrients from various kinds of wastewater. The efficacy varies depending on the kind of microalgae used for each effluent and the growing system used, although it has been shown that open systems offer more satisfactory yields for the removal of nitrogen and phosphate than bioreactors.

Phycoremediaton: Microalgae's special qualities have attracted a lot of scientific interest in its use in the bioremediation of PC-contaminated effluents. These include rapid growth, readily controlled amounts in processing streams, photosynthetic activity that harvests CO_2 from sunlight, and concurrent biomass production that produces high-value goods like soil improvers and biofuels. This metabolic capacity gives mixed crops, in particular, the flexibility they need to survive and thrive in challenging environments. Microalgae remove and degrade PCs through a combination of intracellular and external biodegradation, bio-adsorption, and bio-accumulation.

Bio-Adsorption: The hydrophobic structure, active ingredients, and microalgae type of PCs are necessary for the extracellular mode of bio-adsorption. Because they contain amines, phosphates, carboxylates, and other polymer lattices that resemble cellulose, pectins, hemicelluloses, proteins, and lignin, microalgae have negatively charged cell walls. For example, progesterone and norgestrel cells of *Scenedesmus obliquus* and *Chlorella pyrenoidosa* have been identified, and the adsorption of active compounds, such as ibuprofen, metoprolol, diclofenac, and paracetamol, by various microalgae has been reported to range from 0 to 16.7% (Xiong *et al*., 2017).

Bioaccumulation: Microalgae absorb organic contaminants along with the nutrients they need to flourish through a metabolic process known as bioaccumulation. In contrast, Desmodesmus subspicatus collects about 23% of radiolabeled 17α-ethyleneestradiol (14C-EE2) over a 24-hour period, while *Chlamydomonas mexicana* and *Scenedesmus obliquus* accumulate carbamazepine (Xiong *et al*., 2017).

Biodegradation: By catalysing the breakdown of complex compounds in their environment into simpler molecules, biodegradation is a superior method for microalgae to reduce the organic load. Examples of intracellular biodegradation include S. obliquus and C. pyrenoidosa, which biodegraded 95% of the progesterone concentration in an aqueous medium. Additionally, it has been noted that 30-80% of the drugs ibuprofen, caffeine, and carbamazepine are biodegraded by microalgae in urban wastewater (Xiong *et al*., 2017). Microalgae produce extracellular polymers (EPs) that are discharged into the environment, such as proteins, enzymes, and polysaccharides. As the accumulation of nutrients from negatively charged proteins and polysaccharides occurs, xenobiotics are also absorbed and neutralise toxic chemicals present in the microalgae growth media.. Meanwhile, the by-products generated have an impact on internal cell degradation (Xiong *et al.*, 2017). The degree of removal efficiency of active pharmaceutical ingredients (APIs) varies from zero to complete and is dependent on the kind of microalgae, culture technique, operational parameters, and physicochemical properties of the active substance (Fig. 2).

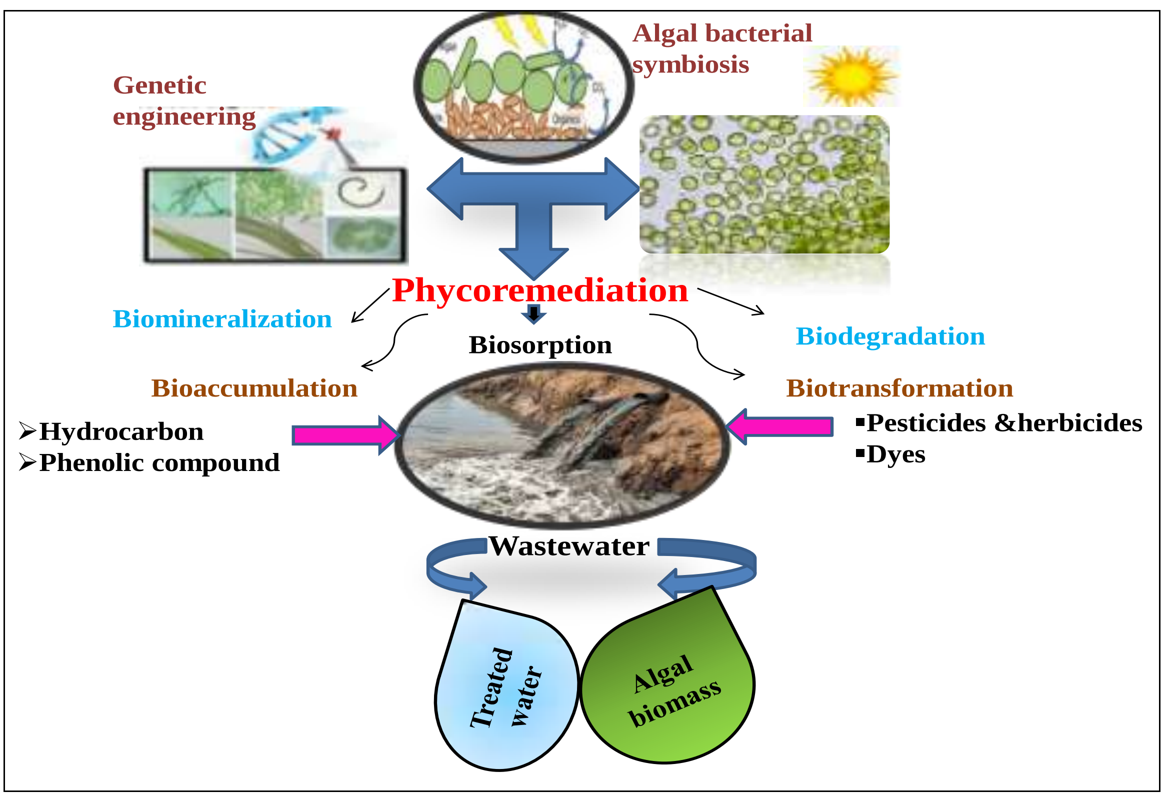

Fig. 2 : Procedure for using biomass, cyanobacteria, microalgae, and other microbes to biodegrade, accumulate, biomineralize, and convert organic contaminants.

Algal carbon capture and utilization: The biomass of microalgae is highly valuable for sequestering CO_2 since it may be utilised in a variety of ways, including as animal feed, biofertilizer, or as a feedstock for biofuel. This allows for the introduction of resource recycling. Numerous microalgal strains have been investigated for CO_2 sequestration. The table indicates that the sequestration rate might vary between 0.39 and 51.5 g L^{-1} d^{-1}. This demonstrates that biomass growth has a direct impact on the carbon sequestration capability of microalgal strains, and depending on the strain, biomass composition may also have an impact. Additionally, because of its faster growth rate, *Chlorella* sp. is the most favoured microalgal strain for CO_2 sequestration investigations; it is observed that *Chlorella minutissma* grew five times faster than *Euglena*, also confirms that microalgae may be a great tool for forced CO_2 sequestration and that CO_2 from industrial chimney waste flue gas may be obtained for use in microalgal photobioreactors (Bhowmick *et al.*, 2019).

Studies have indicated that large concentrations of sulphur oxides, nitrogen oxides, dust, or high temperatures in the input gas can have a significant negative influence on the effectiveness of CO_2 bio sequestration. Hundreds of additional chemicals have been detected in the gases that are fed into photobioreactors (PBRs) besides CO_2, and it is still unclear how these substances impact the efficiency and photosynthetic process. It makes sense to believe that a large number of them will harm, impede, or poison the microalgae as they grow.

Microalgae are able to metabolise NO_x at low quantities, and it does not impede their metabolic processes. However, microalgae are hazardous to SO_x (Mustafa *et al.*, 2021). According to a research by Stewart & Hessami a 4000 m^3 open system might eliminate 22,000 mg of CO_2 annually. The microalgal biomass absorbed NO_x as growth nutrients. Less than 60 ppm of SO_x should be detected in the input gas (Stewart *et al.*, 2005). CO_2 capture and utilization is a cutting-edge strategy that integrates resource conservation and environmental preservation in wastewater treatment operations. The primary cause of WWTPs' large CO_2 emissions is the biological breakdown of organic materials in wastewater. By using CO_2 capture and utilization technology, a circular economy can be created by reducing emissions while simultaneously turning the captured CO_2 into useful products (Fig. 3).

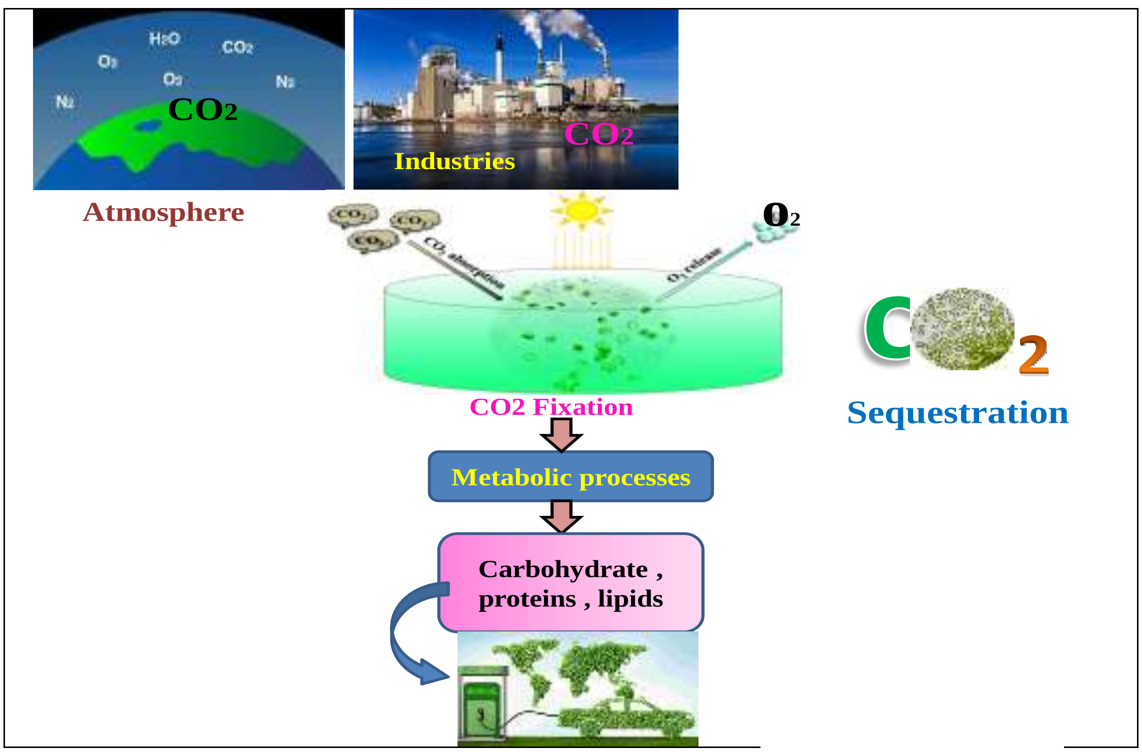

Fig. 3 : Utilising microalgae to sequester carbon dioxide (Okeke, E. S., *et al.*, 2022)

Algal species associated with wastewater treatment

Following the initial procedure, biological treatment is typically employed as a follow-up therapy to eliminate pollutants that are primarily biodegradable. Many genera of microalgae, including Phormidium, Scenedesmus, Chlorella, Botryococcus, Limnospira, and Chlamydomonas, have been identified as outstanding bioremediation agents. Scenedesmus, Chlorella, Euglena, Oscillatoria, Chlamydomonas, and Ankistrodesmus have all shown effective growth and exceptional resistance to toxins (Hosseinzadeh *et al*., 2022). According to Sheehan *et al*. (1998), microalgae come in over 3000 distinct strains, each with special qualities and the capacity to remediate wastewater. However, when selecting a strain or mix-consortia for wastewater treatment, the most crucial factors to take into account would be

- the effluent's properties,
- The required level of treatment efficiency,
- The energy and cost of harvesting biomass, and
- Using the harvested biomass.

For the following reasons, choosing the right microalgae species is crucial to the whole production process' success (Bastos, 2018).

- Ability to withstand short-term stress, particularly in closed photobioreactors;
- To obtain greater control over contaminating microbes;
- High photosynthetic efficiency, or the ability to absorb CO_2 in photoautotrophic systems;
- The ability to tolerate significant temperature swings brought on by daily and seasonal cycles;
- Less need for nutrition;
- Possibility of obtaining co-products with high value addition to the intended items.
- Existence of brief cycles of productivity;
- Demonstrate auto flocculation, which is helpful for the stage of micro algal biomass recovery.

Algae-inspired heavy metal removal

The most basic element for all living things is water, which also serves as a great solvent. The presence of dangerous contaminants, such as heavy metals, in the water will cause the biotic systems in aquatic environments to be negatively altered. Industrial and agricultural sites are the primary sources of streams contaminated with heavy metals, with household sewage coming in second. In addition, some undesirable metals may be introduced to open waterways by specific natural events such volcanic eruptions and land erosion FodayJr *et al.* (2021). One of the most important environmental issues of our day is heavy metal contamination. Heavy metal-containing wastes are produced and released into the environment by a variety of industries and activities, including mining, tanneries, smelters, manufacturers of energy and fuel, chemical, and electroplating. Accordingly, metal contamination is bad for the ecosystem and for human health (Wang & Chen *et al.*, 2006). The metals classified as heavy have a very high density and are extremely toxic even in little amounts. These heavy metals include mercury (Hg), cadmium (Cd), arsenic (As), chromium (Cr), thallium (Tl), zinc (Zn), nickel (Ni), copper (Cu), and lead (Pb). Municipal wastewaters, industrial wastewaters, landfill leaches, urban runoff, and mining wastes are the main causes of contamination. Burkhard *et al.*, 2000) (Table 1)

Table 1 : Microalgal removal of metals from wastewater (Al-Jabri *et al.*, 2020).

Metals	Strain	Initiial Conc. (mg/L)	pH	Temp. (°C)	Time (Hour)	Removal Efficiency (%)
Cadmium	Scenedesmus sp	0.5	6.2–6.5	25	24	73
	Chlorella sp.	100	7.4	-	24	33–41
	Chlorella vulgaris	5	6.2–6.5	25	24	66
Chromium	*Chlorella vulgaris*	227	0.5-5	24	6	50.7-80.3
	Scenedesmus *sp*	10	0.5-5	-	0.5-5	92.89
	Spirullina sp	10-100	2-6	-	0.17-5	82.67
Copper	*Spirullina maxima*	56.6	7.96	26-28	240	94.9
	Chlorella vulgaris	56.6	7.9	26-28	240	96.3
	Scenedesmus *obliquus*	60	5.5	30	1080	72.4-91.7
Lead	*Chlorella vulgaris*	10	6	-	-	89.26
	Chlorella sp.	1-50	8.1-8.6	28	288	66.3
	Psuedochlorococcum typicum	10	7	20	24	70
Mercury	*Chlorella vulgaris*	0.3- 0.8	-	18-21	-	79-86
	Chlorella vulgaris			35	0.17-0.35	34.21-93
	Psuedochlorococcum typicum			20		97
Nickel	Scenedesmus *sp.*	30	6.0-7.2	-	5	97
	Chlorella vulgaris	10-40	7.4	-	24	33-41
	Chlorella miniate	30	6.0-7.2	-	5	60-73
Zinc	Chlorella sp.	1-50	8.1-8.6	28	288	60-70
	Synechocystis sp	30	6.0-7.2	-	5	40
	Scenedesmus sp.	30	6.0-7.2	-	5	98

Algal biomass used in treating waste water

Research and development (R&D) on algal production examines the availability and use of resources, the development and enhancement of algal biomass, the characterization of algal biomass constituents, and the ecology and engineering of cultivation systems. High rate algal ponds (HRAPs), which are also used to treat wastewater, are often the sites of biomass from microalgae production related to wastewater. However, The vast majority wastewater types contain large concentrations of bacteria, which might impede the growth of algal biomass by posing a competition for nutrients and space Santiago *et al.*, 2013) CO_2 to high rate algal ponds (HRAPs) to promote algal production. Biofuel can be produced from the harvested algal biomass by-product of this method. Aerobic bacteria use the oxygen in wastewater to convert waste into CO_2, phosphate, and ammonia, which are then absorbed by new algal biomass. This explains why wastewater is ideal for the growth of naturally occurring algae. Low C:N ratios in wastewater suggest that, when additional CO_2 is added to HRAP, all of the N in the wastewater will be converted to algal biomass. As stated by Benemann, J. R., Lundquist, T. J., and Craggs (2012). An average algal productivity of 16.7 g/m^2/d for the HRAP4d (4 d HRT), a maximum of 24.7 g/m2/d recorded in January 2008, and 9.0 g/m^2/d for the HRAP8d (8 d HRT) were obtained by adding CO_2 to the wastewater treatment HRAPs.

Using basic gravity settling equipment, the algae biomass produced in the HRAPs was efficiently collected (mean harvested algal productivity: 7.5 g/m^2/d for the HRAP8d and 11.5 g/m^2/d for the HRAP4d).Harvest ability was higher (83%) for the HRAP8d biomass due to its higher bacterial composition and greater algal/bacterial floc size than the HRAP4d biomass (69%) Park *et al.*, 2010). For many methods, the production of algal biomass is still in its infancy. Algae use CO_2 as their primary carbon source through a variety of internal metabolic activities. Since microalgae fix carbon and convert it into biomass, CO_2 is a precursor to the synthesis of proteins, lipids, and carbohydrates. These components are regarded as the foundation of numerous beneficial applications derived from algae, particularly the synthesis of biofuel, human and animal nutrition, animal feed, and bioremediation instruments for wastewater treatment Moghazy *et al.*,2022).

Accessing Algal biomass

Recycling nutrients is necessary for wastewater reclamation to achieve environmental sustainability. Given that producing N and P fertilisers requires a significant amount of energy (11.1 kWh kg^{-1}and 10 kWh kg^{-1}, respectively), Olsson (2015). In addition to being sustainable, recycling N and P will save a substantial amount of energy globally. As previously said, algae are very effective in eliminating pollutants like heavy metals, medications, and newly discovered contaminants, which is crucial for wastewater reclamation. However, as was already indicated, the algal biomass will accumulate these pollutants. As a result, algae grown in wastewater and some flue gases do not provide biomass appropriate for use as food, feed, or even biofertilizer. As a result, algae cultivated on polluted wastewater and flue gases should be used as a bioenergy source, with the pollutants being removed or converted into energy-rich compounds before being separated or concentrated in ashes (Fig. 4).

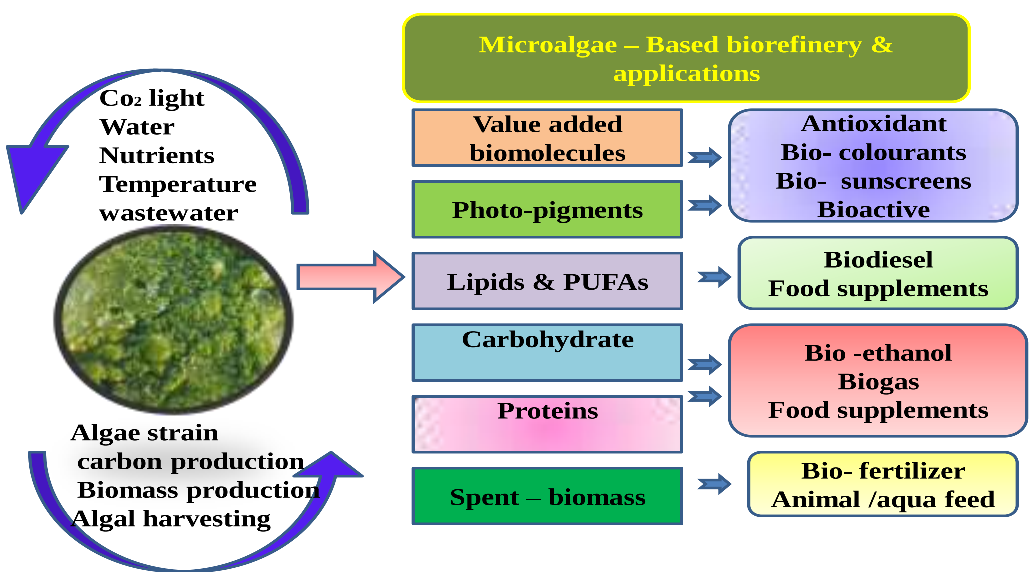

Fig. 4 : General Scheme of Microalgae Based Biorefinery & Circular Economy

Algal biomass related to biofuels bio-ethanol, biogas, and biodiesel

The growing global population is raising energy demands and raising questions about the sustainability of fossil fuels, particularly in nations with limited access to them. The main factor driving the increased interest in fossil fuels is the perception that renewable biofuels are the most likely to replace them in transportation. Consequently, a number of nations have already mandated the production of biofuel, demonstrating its immense potential to enhance the sustainability of the energy sector (Table 2).

Table 2 : Shows Algal biomass related to biofuels bio-ethanol, biogas, and biodiesel

Microalgae	Wastewater	Biofuel	Ref.
Microalgae consortium	Dairy	Biodiesel	Chandra, R.; Pradhan, *et al.* (2021)
Chlorella vulgaris	Textile	Biodiesel	Fazal, T.; Rehman *et al.* (2021)
Chlorella sp	Urban	Biogas	Vargas-Estrada *et al.* (2021)
Chlorella vulgaris, Tetradesmus obliquus and Chlamydomonas reinhardtii	Piggery	Biogas	Molinuevo-Salces (2016)
Chlamydomonas reinhardtii UTEX 2243 and Chlorella sorokiniana UTEX 2714	Acetate rich wastewater	Biohydrogen	Hwang *et al.* (2021)
Chlorella vulgaris, Tetradesmus obliquus, Microalgae consortia	Urban	Biohydrogen	Batista (2015)
Wild yeast and microalgae consortium	Municipal	Bioethanol	Reyimu, & Özçimen, (2017).
Nannochloropsisoculata and Tetraselmis suecica	Municipal	Bioethanol	Walls; Velasquez-Orta,
Tetradesmus obliquus	Brewery	Bio-oil, BiocharBiogas	(Ferreira, Ferreira, Dias, & Gouveia, 2020)

Chandra *et al*. evaluated the biodiesel production potential of a microalgal consortium comprising Mychonastes homosphaera (formerly known as *Chlorella minutissima*), Desmodesmus abundans, Nostoc muscorum, and Arthrospira cultivated in a medium containing 70% dairy wastewater supplemented with 10 g L^{-1} of glucose. Azal *et al*. (2021) evaluated the production of biodiesel from microalgae biomass produced in wastewater, specifically textile WW, using the microalgae *Chlorella vulgaris.* More of the fatty acids that are ideal for biodiesel production, namely palmitic acid (C16:0) and linolenoic acid (C18:3), were found.

Biogas can be produced from microalgal biomass by combining anaerobic digestion with methanogenic bacteria. Cell walls are first hydrolysed, increasing the amount of biogas produced (Passos & Uggetti, 2014). *Tetradesmus obliquus* biomass can be used to produce biogas with a yield of 287 mL biogas gVS^{-1} and *Chlamydomonas rehardtii* with a production of 587 mL biogas gVS^{-1}. According to Batista *et al*., a microalgae consortium that was obtained via the process of dark fermentation of municipal wastewater to produce biohydrogen included Tetradesmus obliquus and *Chlorella vulgaris*. The microalga that produced the greatest H2 (56.8 mL H_2 g^{-1}) was S. obliquus, and its biomass when grown on synthetic media yielded a value similar to that.

Microalgae species with a high carbohydrate content can make bioethanol by using yeasts to ferment sugar. Miranda *et al*. (2012) and Kim, Oh (2017). The batch culture of *Tetraselmissuecica* and *Nannochloropsis oculata* in municipal wastewater was studied by Reyimu *et al*. (2017) in order to produce bioethanol. Ferreira *et al*. (2020) demonstrated that Tetradesmus obliquus biomass produced in various WWs, such as the urban, dairy, and brewing sectors, as well as cattle and poultry breeders, could be pyrolysed to produce biochar, bio-oil, and biogas. It was discovered that there was a notable concentration of aromatic chemicals in the bio-oil that was produced, with yields ranging from 30 to 60% (w/w). The WW brewery's biomass allowed for the extraction of biogas (6%), charcoal (30%), and bio-oil (64%).

Algal bioplastics and biopolymer

Large quantities of lipids, proteins, and carbohydrates the most important components of the primary composition of biobased products including bioplastics, biopolymers, and biobased polyurethane can be produced by microalgae (and some cyanobacteria). Mehta and associates (2017) and Mata (2010). Recently, microalgal biomass has been recognised as a possible source of materials to improve a variety of businesses, including the manufacturing of bioplastics. It can be used as a feedstock for a subsequent process or directly as biomass Rahman *et al*., 2017. Incorporating sociological and political considerations into discussions about the impact of plastics has been essential for all parties involved. Jennifer Perr also emphasises how critical it is to have a circular economy for these goods.

Algal nutraceutical and functional foods

Combining the terms "nutrition" and "pharmaceutical," the term "nutraceutical" refers to nutritionally related substances with physiological benefits associated with the prevention and/or defence against chronic illnesses. Nutraceuticals are mixtures and unadulterated ingredients taken from herbs, as well as dietary derivatives, which are altered meals including cereals, sauces, spices, and beverages that offer health benefits. Because microalgae produce a wealth of bioactive compounds, including antioxidant molecules and carotenoids with proven health benefits (Galasso *et al*., 2017), they also have great potential for use in the field of functional foods. Since the synergy between multiple families of bioactive chemicals significantly increases their beneficial effects on health, this characteristic offers an extra advantage. I. Hamed and F. Özogul (2015). Because of their high abundance of pigments (like lutein and β-carotene), vitamins (like B12), important amino acids (like leucine, isoleucine, and valine), and polyunsaturated fatty acids (like PUFAs n3 and n6), marine microalgae are currently being used as functional foods. It has recently been suggested that microalgae biomass be added to wheat flour to enhance its quality for making pasta and related goods, or it can be used as a supplement in ready-to-use dry milk products (such high-protein beverages and baby soups) that now utilize soybean as their main ingredient Wells *et al.,* 2016).

Algal soil conditioner and natural fertiliser

Because of its high concentration of micro- and macronutrients, bioactive compounds, and phytohormones, which produce positive biochemical effects in the soil ecosystem as a result of interactions between crops and the soil microbiome (Marks *et al.*, 2019), there is growing interest in using microalgae biomass as a potent biofertilizer on agricultural land. Furthermore, microalgae are microorganisms with a high specific absorption rate, which may develop and assimilate phosphorus and nitrogen in settings with restricted nutrient supply due to their exceptional capacity to recover nutrients for their metabolic activities De Souza *et al.*, 2019).

The use of live cyanobacteria and microalgae as biofertilizers improves crop growth and production yields by producing mineralisation effects, mobilising organic and inorganic nutrients, and producing a variety of secondary metabolites with beneficial properties such as growth hormones, polysaccharides, antimicrobial compounds, and many others (Nichols *et al*., 2020). Microalgae are also known as biocontrol agents or biopesticides because of their ability to create biocidal substances such as benzoic acid and majusculonic or hydrolytic enzymes, which can be utilised to control or impede the growth of pathogens such as fungi, bacteria, and nematodes Renuka, Singh, & Bux, 2018).

Conclusion / final verdict

Because of the world's rapid economic and population growth, there is a scarcity of water resources suitable for direct human consumption. Water cleanup will, therefore, unavoidably take centre stage on a global level. Various types of wastewaters can promote the growth of microalgae. They have a high potential for removing contaminants from municipal and industrial effluents. This research focusses on the most recent advances in WW cleaning using microalgae cultivation. Microalgae-based wastewater treatment (WWT) has already gained attention due to its low energy requirements, strong capacity to grow in a variety of environmental conditions, and potential to transform WW nutrients into high-value compounds. It was determined that microalgae-based WWT is a sustainable and cost-effective alternative. Furthermore, microalgae remove several types of toxins by biosorption, bioaccumulation, and biodegradation. Toxins from agricultural runoff and industrial effluent from the pharmaceutical and textile industries are two examples. Microalgae can use the micronutrients found in effluents to reduce carbon dioxide emissions.

Highlights

- Algae are capable of treating wastewater and cleaning up contaminants.
- Algal cultures harvest biomass from the contaminants found in wastewater.
- Value-added products can be fractionated using the algal biomass.
- Potential algae have implications for sustainability and resource recovery.

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