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Waste Algae for Bioenergy Generation to Mitigate Eutrophication and Greenhouse Emissions in Water Bodies

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Abstract

Eutrophication has a significant negative impact on the ecosystem since it depletes the planet's biological resources and is further responsible for climate change. It is caused by both endogenous and exogenous nutrient enrichment. This phenomenon degrades the water quality and simultaneously increases the greenhouse gases emission from waterbodies resulting in climate change Inland waterbodies contain enormous amounts of nutrients such as phosphorous, nitrogen, and carbon. Thus, it becomes essential to restore these nutrients using proper sustainable approaches. Algae-based technologies have received a lot of attention these days because of environmentally friendly and inexpensive treatment. About 70% of the nutrient load from wastewater can be removed using such technology. The recovered algal biomass after wastewater treatment contains various biomolecules which can be used for the producing of value-added products such as bioenergy in the form of biomethane and biodiesel, cosmetics and pharmaceuticals along with the synthesis of nanoparticles. Therefore, the primary goal of this review is to inform readers about the possibilities of a low-cost integrated biorefinery based on microalgae for resource recovery and to mitigate eutrophication and greenhouse gas emission from water bodies.

Keywords

eutrophication, nutrient, algae, bioenergy, resource recovery, greenhouse gases

1 Introduction

Due to increased urbanization and industrialization, overpopulation is causing an increase in environmental degradation around the world. Although human activities have advanced civilization to a new level, non-renewable sources are rapidly decreasing, and a vast quantity of wastewater (WW) is also being generated. WW contains a high concentration of organic and inorganic compounds like fats, proteins, carbohydrates, nitrate, and phosphate etc., along with some toxic compounds. These compounds cause water pollution and algal growth in the waterbody. Due to the high amount of phosphate and nitrogen in WW, algal blooms frequently occur and thus impact the food chain. Biotoxins made by algal blooms build up in the food chain, from the primary consumer onwards. The rapid rate of oxygen depletion resulting from algal respiration inflicts severe hypoxic stress on aquatic life, ultimately leading to formation of "dead zones". Besides creating the dead zones, these algae can be effectively utilized for the production of various compound and energy driven molecules. Based upon the algal composition, different algae can be used to produce biofuels. For example, *Nannochloropsis*, *Chlorella*, and *Botryococcus*, are known for their high lipid content, which can be converted into biodiesel through a process called transesterification, similarly algae with high in carbohydrates, such as *Chlorella*, *Spirulina*, and *Scenedesmus*, can be used to produce bioethanol through fermentation. Microalgae can also be used to produce bioelectricity through a process called microbial fuel cell (MFC) technology, where bacteria consume the organic matter produced by the algae and generate electricity. Anaerobic digestion (AD) of certain types of algae, such as *Cladophora* and *Ulva*, produces biogas, which is primarily composed of methane [1]. Algal biomass has the potential to produce a high yield of biofuels per unit area, but

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its high production costs remain a significant barrier to its commercialization. The cost of producing algal biofuels is influenced by factors such as the cost of algae cultivation, harvesting, drying, and conversion to biofuels. The economic viability of algal biofuel production can be improved by using waste streams or wastewater as a nutrient source, as well as by developing more efficient and cost-effective harvesting and conversion technologies. The life cycle assessment of algal biofuels shows that the economic and environmental performance is influenced by factors such as cultivation methods, harvesting technique, and processing technology. While algal biofuels have the potential to reduce greenhouse gas emissions, their economic viability still needs improvement to make them a competitive alternative to fossil fuels. Thus, further research is needed to identify the most cost-effective and efficient technologies for algal biofuel production, and to develop strategies for reducing production costs. Additionally, the environmental benefits of algal biofuels compared to fossil fuels are an important consideration. Algal biofuels have the potential to reduce greenhouse gas emissions and improve energy security [2]. Moreover, algae cultivation also benefits the environment as it consumes CO_2 as the carbon source for photosynthesis process, thus it can combat CO_2 released from human activities and reduce the amount of greenhouse gases (GHGs) [3]. Algal biomass can be used for carbon capture and storage (CCS) by cultivating algae in open ponds or closed photobioreactors and then burying the harvested biomass in geological formations or using it as a soil amendment. Additionally, the production of biofuels from algae can also contribute to carbon sequestration by displacing fossil fuels. However, carbon sequestration potential of algae needs to be evaluated in the context of a life cycle assessment to ensure that the overall environmental benefits are realized [4]. Microalgae contain high levels of antioxidants, vitamins, and fatty acids, making them attractive for use in skincare and haircare products. Additionally, microalgae-based ingredients have also been used in haircare products to promote hair growth and reduce hair damage. A study suggested that the use of algae in cosmetics is a growing market and has the potential to contribute to the economic viability of algal cultivation [5]. Indeed, waste biomass, or WW, has stimulated the interest of academics/researchers in the pursuit of sustainable resource recovery. The purpose of this review is to suggest a potential approach to lowering industrialization's negative environmental impact and securing energy generation through algae.

2 Inland waterbodies – vital resource for life

Water is one of the basic and vital requirements of life to thrive on earth. Water is distributed all over the globe in different type of water bodies in a very complex manner [6]. Distribution depends upon the quality of water, climatic conditions of region, availability of water, anthropogenic activities, dam construction and several miscellaneous factors. Water bodies are home to a variety of species and serve as important habitats for fish, birds, amphibians and other forms of wildlife. They also provide recreational opportunities for people who use them for fishing, swimming or boating. Furthermore, these water bodies can be used for irrigation purposes and to generate hydroelectric power. The importance of waterbodies is summarized in Fig. 1.

According to Gleick [7], approximately 71% of earth's surface is covered with water. 96.5% of the earth's water is stored in oceans. Around 2.5% of the total is fresh which further distributed in glacial form (68.7%) followed by ground water (30.1%) and surface water (1.2%). The surface freshwater breakdown from this 1.2% is displayed as a pie chart (Fig. 2). An extra 20.9% of this water is found in lakes, the majority of which is covered in ice. 0.49% of the freshwater on the surface is found in rivers. Although rivers only make up a small fraction of freshwater, they provide a significant portion of human water needs. This inland water evolves carbon dioxide, methane and nitrous oxide which causes greenhouse effect and is one of the major global climatic problems. 20% of the world's CO_2 emissions from fossil fuels come from GHG emissions from lakes and impoundments (9.3 Pg $C\text{-}CO_2$ yr^{-1}) [8]. $C\text{-}CO_2$ represents carbon dioxide equivalent (CO_2eq) emissions in terms of carbon (C) content. Increased in population, urbanization, industrial expansion has adversely affected the inland waterbodies such as lakes, ponds, rivers etc. These impoundments are easy target for dumping waste and thus discharge of treated or untreated waste promotes eutrophication. Inland waters are essential for human life, but they are also vulnerable to the effects of climate change. As global temperature rises, lakes are becoming increasingly threatened by rising greenhouse gas emissions. Recent studies show that the levels of carbon dioxide and other greenhouse gases in the atmosphere have increased by over 40% since pre-industrial times [9–11]. This is causing inland waterbodies around the world to become more acidic and warmer, with serious implications for aquatic life and ecosystems. Furthermore, these changes in water temperature can also lead to increased flooding and droughts in some areas. It is therefore essential that we take

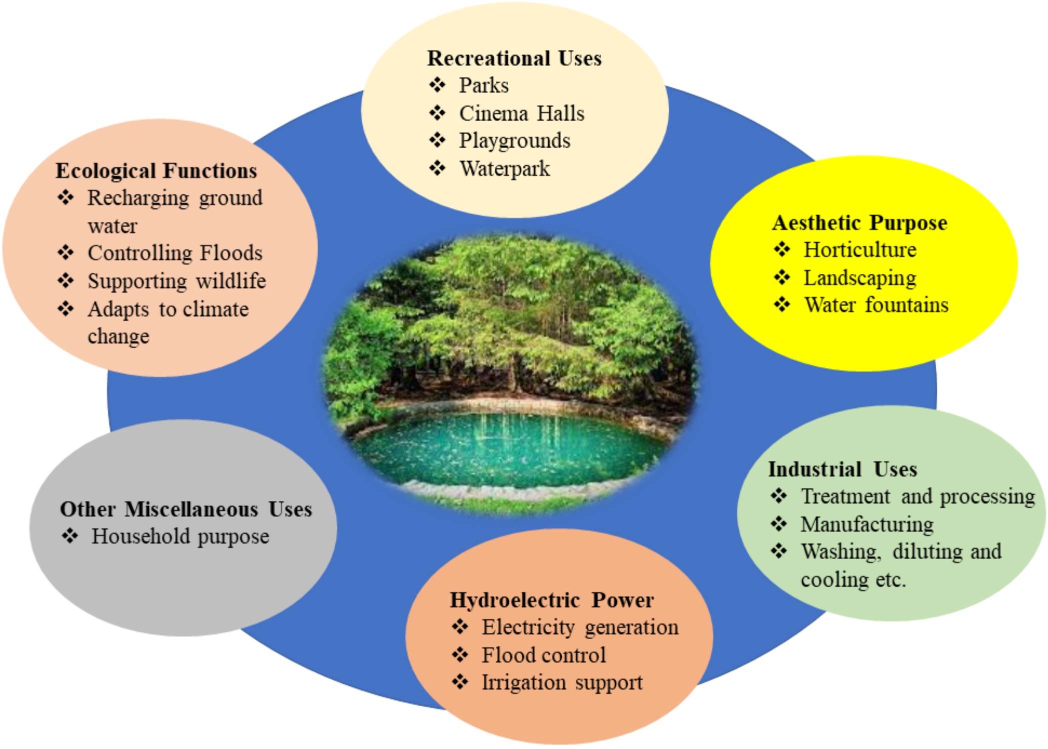

Fig. 1 Schematic representation of various functions offered by water bodies

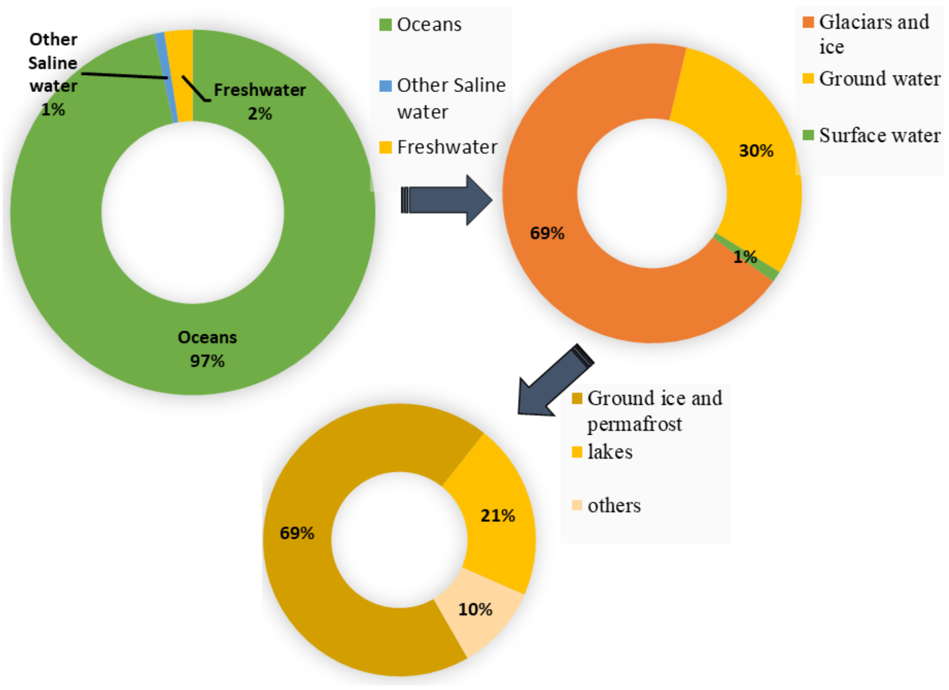

Fig. 2 Global water distribution

action to reduce our emissions in order to protect our water sources from further damage.

3 Eutrophication in water bodies

When nutrient like nitrate and phosphate increases along with favorable conditions water bodies suffer from eutrophication. This phenomenon includes Harmful Algal Blooms (HABs) and anoxic events [12]. HABs are harmful for the waterbodies because it produces toxins and excess biomass (algae). Excess biomass covers the top surface of waterbody and decreases the light penetration which eventually results into less dense submerged aquatic vegetation [13]. When this access biomass starts decaying it triggers high oxygen consumption and causes mortality of aquatic life [14]. Eutrophication is influenced by a multitude of interacting factors, making it difficult to account for every individual factor. Table 1 [15] illustrates the major known contributors to eutrophication. The pathways for GHG emissions are impacted by a few composite elements that can either accelerate (+) or decelerate (−) emissions. These elements can be categorized into primary and secondary parameters. Primary parameters include climatic conditions such as wind speed, precipitation, water temperature, and run [16, 17]. On the other hand, secondary parameters consist of dissolved oxygen (DO), organic matter (OM), and other water parameters such as the average depth, reservoir age, thermal stratification, nutrients (C, P, N) and their ratios, carbon-nitrogen content, nitrogen-phosphorous content, carbon-nitrogen ratio, total nitrogen content, total phosphorous content, etc. [18, 19]. GHG emissions exhibit a significant correlation with various factors such as DO, fertilizer content, pH, wind speed, mean depth, water temperature, and thermal stratification. However, the correlation of each factor with GHG emissions can be different. For example, pH has a strong correlation with CO_2 but has a positive relationship with N_2O. Methanogens can produce CH_4 in a pH range of 6 to 8, but they are sensitive to it. CO_2 released during respiration converts to carbonic acid, leading to a decrease in the pH of water bodies. Alkalinity, total dissolved solids, DO, and pCO_2 have a negative association with pH. The relationship between pH and N_2O emission is complex. The pH range between 7–8 is where denitrification produces the most N_2O [20]. Positive and negative correlation of factors reflected in the Table 1.

3.1 Effect of eutrophication over GHG emissions from inland water

Eutrophication have direct as well as indirect impact on GHGs emission form the waterbodies (Fig. 3). Direct emissions relate to water quality parameters such as dissolved oxygen, nutrient loading and organic matter present or biotic components [21–23]. Growth of algal blooms affects water chemistry and aquatic ecosystem which may increase GHGs and falls under indirect emission. In benthic zone anaerobic conditions prevails due to lack of oxygen and methane is hence form as a product of biomethanation (Fig. 3). Methane emission pathway is generally ebullition. Due to the mineralization of carbon from OM and the consumption of oxygen (O_2) by methanogens, CO_2 is produced [17]. Generally nitrous oxide (N_2O) emission is very less from lakes but if waterbody receive agricultural runoff with high content of fertilizers or waste with high nitrogen percentage, it may accumulate and increase N/P ratio, this lowers the DO content and promotes denitrification, allowing for the formation and emission of N_2O. Khoiyangbam and Chingangbam [20] carried out a study in North India and detected a considerable seasonal change in DO, but no relationships between N_2O emission and DO were seen. The shift in dominating primary producers and the bloom of toxic algae are two major factors that influence how eutrophication indirectly affects GHG emissions. Macrophytes produce CH_4 emissions in three stages:

1. As a result of diffusion, emerging plants release CH_4 into the atmosphere.
2. Methanotrophic bacteria work to oxidize CH_4 on the surface of macrophytes.
3. Methanotrophic bacteria that provide oxygen to sediments carry out the decreasing bio methanation process.

Table 1 Factors affecting eutrophication (Adapted and modified from Mondal et al. [15])

Factors	Range	Effect on CH_4	Effect on CO_2	Effect on N_2O
Sulphate	13.2–25 mg L^{-1}	Negative Impact	-	Positive Impact
Dissolved Oxygen	2.23–16.69 mg L^{-1}	Negative Impact	Negative Impact	Positive Impact
	2.80–8.65 mg L^{-1}	-	-	Non-significant
Total Phosphorous	0.00–2.52 mg L^{-1}	Positive Impact	Positive Impact	Positive Impact
	2.17–7.10 mg L^{-1}	-	-	Positive Impact
pH	6.95–8.34	Non-significant	Non-significant	-
	6.90–9.10	Negative Impact	Negative Impact	Negative Impact
	6.54–7.92	-	-	Positive Impact
Age of the reservoirs	Less than 10 years	Positive Impact	Positive Impact	Not reported
Mean depth	5–23 m (shallow)	Positive Impact	Negative Impact	Not reported
Total nitrogen	1.81–57.70 mg L^{-1}	-	Positive Impact	Positive Impact
	0.24–2.01 mg L^{-1}	-	-	Positive Impact

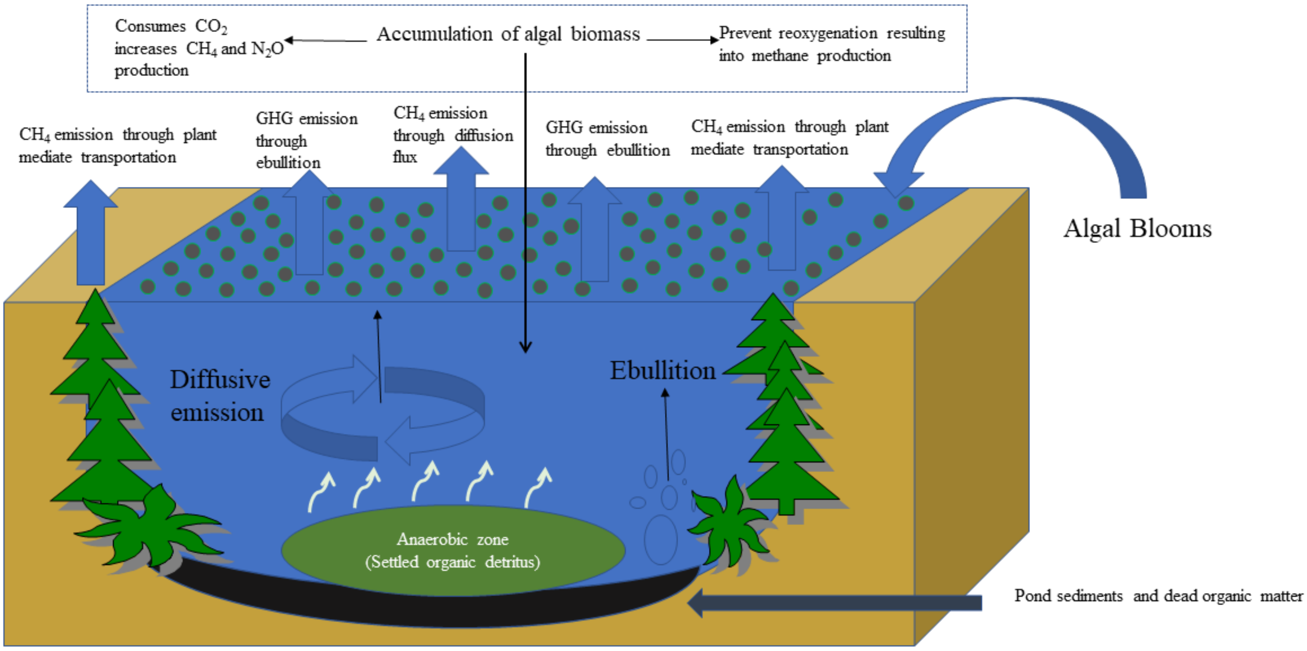

Fig. 3 Schematic representation of various mechanisms involved in the GHG emission from inland waterbodies

According to a report published by [24], algal blooms are expected to become more common during the following several decades as a result of population growth and the substantial GHG emissions that inland waterbodies will produce. GHG emissions from inland waters equal 20% of the world's CO_2 emissions from fossil fuels (9.3 Pg C-CO_2 yr^{-1}) [8] and with the continuous eutrophication of Earth's lentic ecosystems, emissions will increase even more. Emissions vary with the lake size and trophic level. It was estimated that inland waters will emit about 2 PgC yr^{-1} of CO_2, with 1.8 Pg C yr^{-1} originating from rivers and streams and 0.32 to 0.50 Pg C yr^{-1} from reservoirs and lakes [25]. One of the most recent estimates of global GHG emissions from lakes and impoundments found that CH_4 is responsible for about 72% of the climatic impact of GHG emissions (in CO_2-equivalents) from lakes and impounded waters, even though the absolute emissions of CO_2 are 5 to 10 times greater than those of CH_4 and N_2O (in Tg of carbon or nitrogen yr^{-1} [26]). This is due to the fact that CH_4 has up to 34 times the global warming potential (GHG) of CO_2 and is responsible for 20% of the overall increase in atmospheric radiative forcing seen since 1750. CH_4 estimation from lakes and ponds are calculated to be 69 Tg CH_4-C yr^{-1} globally, or 0.85 Pg of CO_2 as CO_2 emission equivalents [27]. Although it is well known that many variables, such as lake depth and sedimentation rates [28, 29], affect the rates of CH_4 emission but the lack of global data on these variables has made it difficult to include them into models for estimating CH_4 emissions. Several lake studies that demonstrate a positive correlation between CH_4 emissions and productivity indicators including total phosphorus (TP) and chl-a. [26, 30, 31]. Moderate global increases in eutrophication could translate to 5–40% increases in the GHG effects in the atmosphere, adding the equivalent effect of another 13% of fossil fuel combustion or an effect equal to GHG emissions from current land use change. Increased eutrophication will elevate the methane evolution by 30–90% in about next 10 years.

4 Waste algae from eutrophicated water bodies possible feedstock for resource recovery

Recovery of resources from wastewater is a global concern that contributes to the circular bioeconomy. Eutrophicated lakes are a major cause of environmental pollution. Algal bloom harvested from such lake is a good source of major organic compounds [32, 33]. These waste algae have also the potential to produce methane (anaerobic digestion) and volatile fatty acids (VFAs). Anaerobic digestion is multifaceted process which involves the breakdown of complex organic compounds into small molecular components with the help of various bacteria [34, 35]. A number of useful bioproducts can be obtained from waste algae harvested from eutrophicated lake. Some of the marketable and useful products from the algae are summarized below.

4.1 Waste algae to marketable products

Waste microalgae can be used in multiple ways such as medical purposes, biofuel, biogas, fertilizer, water treatment aid and biodiesel. The pharmaceutical, nutraceutical, energy and cosmetic sectors may extract numerous high-value compounds from algae [36]. It has a huge scope in global market. By 2024, the global market for products generated from microalgae is projected to reach USD 1,143 million [37]. Algal goods are classified globally as nutraceuticals, dietary and support supplements, medicines, paints, colorants, and other products. Different types of algae and associated marketable products are summarized in the Table 2 [38–58]. Algal-derived coproducts such as astaxanthin, squalene, -carotene, carotenoids, omega-3 polyunsaturated fatty acids (docosahexaenoic and eicosahexaenoic), and phycobiliproteins are increasingly popular in the nutraceuticals and pharmaceutical industries and are a major source of income for algae-producing businesses worldwide. Some algae strains are produced industrially as aquaculture feed due to their high nutrient values and vitality contents. *Spirulina*, *Chlorella*, *Dunaliella*, and *Nannochloropsis* are some examples of microalgae strains used as alternative feeds to traditional aquaculture feeds. *Spirulina* and *Chlorella* are rich in protein, vitamins, minerals, and antioxidants, while *Dunaliella* is high in beta-carotene and other carotenoids. *Nannochloropsis* is rich in polyunsaturated fatty acids essential for fish growth and health. Using microalgae as aquaculture feed can be more environmentally friendly and cost-effective than traditional feeds. These strains can also be used as a source of ethanol, hydrogen, and lipids.

4.2 Waste algae for bioenergy production

Microalgae have become a potential biomass feed for making carbon-neutral biofuels and bioenergy as an alternative to fossil fuels. Similar to a petroleum refinery, a biomass-based biorefinery combines integrated biological and thermochemical conversion processes to create a variety of biofuels, biochemicals, and bioproducts.

4.2.1 Biodiesel

Biodiesel is one of the most valuable products that can be derived from micro-algae. Microalgae can produce biodiesel 200 times more efficiently than traditional crops since they can be harvested after only a few hours to ten days of growing [59]. After using organic solvents to extract lipids from microalgal biomass, algae-based biodiesel manufacturing has been done successfully in laboratory circumstances [60]. It is recommended to maintain an appropriate level of inorganic carbon as well as carbon sources that can be easily hydrolyzed and other readily available nutrients in order to accelerate algae metabolism [61]. Although some species of microalgae, like *Botryococcus braunii* and *Chlorella vulgaris*, have been shown to possess >50% lipid content by dry weight of its mass, making them excellent feedstock for production of biodiesel [62]. Lipids are one of the key components that can be used to produce biodiesel from microalgae. When the lipid content of microalgae is high, it means that there is a larger amount of oil that can be extracted from the microalgae, which can then be converted into biodiesel through a process called transesterification. Although algae biofuels have shown better performance as transportation fuels than fossil fuels, the unit cost of algae

Table 2 Types of algae and associated marketable products

Product	Description	Algae Examples	References
Biofuels	Algae can be converted into biodiesel, Hydrogen, ethanol, methane and bio-oil.	*Chlorella, Nannochloropsis, Dunaliella, Scenedesmus*	[38–44]
Nutraceuticals	Algae contain various nutrients and bioactive compounds that can be extracted and sold as supplements or functional food ingredients.	*Spirulina, Chlorella, Euglena, Haematococcus*	[45–47]
Animal feed	Some types of algae can be used as a feed supplement for livestock and aquaculture.	*Chlorella, Scenedesmus, Nannochloropsis, Isochrysis*	[48]
Fertilizer	Algae can be processed into organic fertilizer, which can be used to enrich soil and promote plant growth.	*Ascophyllum, Ecklonia, Fucus, Laminaria*	[49, 50]
Cosmetics	Algae-derived ingredients are used in various cosmetic products, such as moisturizers, facial masks, and hair conditioners.	*Porphyridium, Chlorella, Spirulina, Dunaliella*	[51]
Bioplastics	Some species of algae can be used to produce biodegradable plastics.	*Chlorella, Spirulina, Euglena, Arthrospira platensis*	[52, 53]
Wastewater treatment	Algae can be used to remove nutrients and pollutants from wastewater.	*Chlorella, Scenedesmus, Desmodesmus, Coelastrella sp*	[54–57]
Carbon credits	Algae-based carbon capture and utilization technologies can generate carbon credits that can be sold in emissions trading markets.	*Chlorella, Nannochloropsis, Scenedesmus, Dunaliella*	[58]

fuels (expected to reach 2.0 to 2.8 USD L^{-1}) is significantly higher than that of fossil fuels (estimated to be approximately 1 USD L^{-1}). In spite of this, it is anticipated that algal biofuels would establish a 75 percent market share by the end of the next decade, according to the present sustainable trend of development [63]. The commercialization of algae-based biofuels depends on the advancement of feasible and algae cultivation, algal oil extraction, and algal to biodiesel conversion sustainable technologies.

4.2.2 Bioethanol

The Weizmann process, also known as ABE (acetone-butanol-ethanol) fermentation, is used to make bioethanol. The various feedstocks used to make this liquid fuel include corn, soybeans, wheat straw, woodchips, and, more recently, microalgae. A number of countries, including Brazil, China, and India, have started making bioethanol for the use as a commercial fuel [64]. Bioethanol is chosen over fossil fuels because of its less environmental impact. As it contains less amount of sulphur than gasoline, and thus lowering the emissions of damaging greenhouse gases during combustion. Moreover, bioethanol contains approximately 66% energy contained by gasoline in the same volume [32]. Algae are one of the most desirable biomasses for the production of bioethanol. As these microorganisms are able to survive in municipal or industrial wastewater [65]. This aids bioremediation since the plants consume CO_2 and other nutrients for photosynthesis, thereby purifying the water [66]. Starch, a storage-related substance, or cellulose can both be fermented to produce bioethanol (a component of the cell wall) [67]. The cell walls of blue-green algae, such as *Spirogyra* species and *Chlorococum* sp., contain large concentrations of reserved polysaccharides [68]. The high carbohydrate content of algae makes them a desirable feedstock for bioethanol production. Common algae used for bioethanol production include *Chlamydomonas, Glacilaria*, *Scenedesmus*, *Euglena gracilis*, *Porphyridium*, *Chlorella*, *Dunaliella*, and *Chlorophyllum* [68].

4.2.3 Biomethane

In the past two decades, various microalgal strains have been extensively explored for biomethane production through AD [69]. Further, microalgal biomass harvested from the wastewater treatment as well as from the eutrophic water bodies has been reported as an excellent feedstock for biomethane production [70, 71]. Consequently, AD of microalgal biomass has emerged as an established, long-term solution for recovering renewable energy from wastewater and eutrophic water bodies. The possible mechanisms and process involved in the AD of microalgal biomass is depicted in Fig. 4. Further, as in the case of other feedstock such as cattle dung, the volatile solid (VS) concentration in the digester plays a crucial role in AD of microalgal biomass. High VS loading results in a considerable reduction of the digester size hence improving the land footprints and the overall economics of the process. However, substrates with a high loading may require

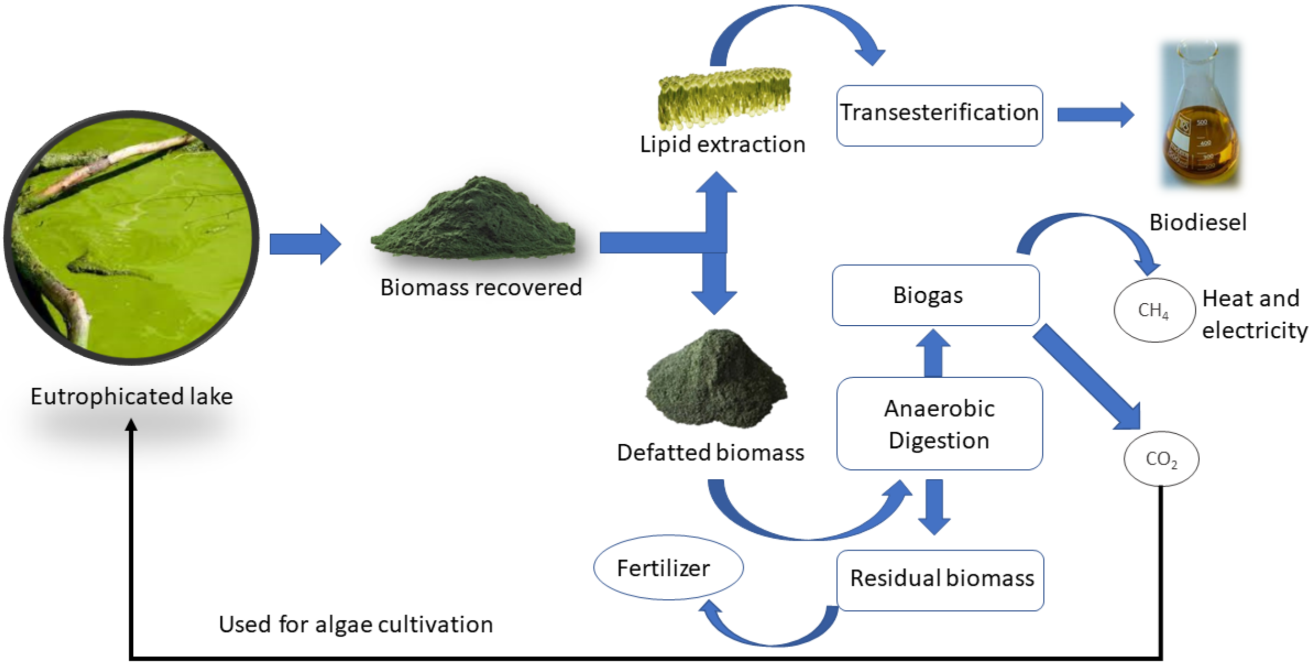

Fig. 4 Flow diagram of effective production of bioenergy through utilization of waste algal biomass from eutrophic water

a longer hydraulic retention time (HRT) for optimal digestion. In addition, at high VS loading, process stability may be reduced, leading to AD failure due to the accumulation of unutilized substrate in the reactor and the reduction of anaerobic microflora [72]. For instance, Gou et al. [73] found a gradual decrease in methane production and VS reduction during the co-digestion of WAS and food waste at higher VS loadings. Moreover, Kumar et al. [74] observed the highest methane yield of 315 mL g^{-1} VS_{fed} was achieved from 5 g VS L^{-1} of volatile solid loading, however, methane yields at the VS loading at 10 and 15 g VS L^{-1}, respectively, were observed to be lower (240 and 224 mL g^{-1} VS_{fed}). Additionally, the amount of biomass that may be converted into biomethane depends on the organic content of the substrates. Despite recent efforts to enhance the AD of algae, several significant obstacles still need to be addressed before it can be applied in real-world situations. Low microalgal productivity of biomass, small carbon-to-nitrogen (C/N) ratio, and a difficult along with complex cell wall because of its chemical composition are some of the main obstacles in microalgal AD [75]. For a successful AD, C/N ratio of biomass should be between 15 to 25 [76, 77]. While the majority of algal species have a C/N ratio that ranges from 4.5 to 8.5. Ammonia (NH_4^+) typically builds up in the digester due to the small C/N ratio of the feedstock. The methanogen activity is then impacted by the stored ammonia, which causes the accumulation of volatile fatty acids (VFAs), which disrupts microbial activity further in the process [78]. The algae-based technology requires only 22% of the energy demand of intermittent-feed activated sludge wastewater treatment systems and has lower global warming and eutrophication potential [79].

4.2.4 Challenges in bioenergy generation

The production of bioethanol and biodiesel using processes like fermentation and transesterification faces several bodies challenges, as highlighted by Osman et al. [2] one significant challenge is the availability and cost of raw materials. Rapeseed, soybeans, and sunflowers are said to be efficient feedstock for the production of biodiesel, while sugar-based crops like sugar beetroot and sugarcane contain a significant amount of saccharose that can be extracted and fermented into bioethanol [2, 3]. For instance, research have shown that the price of corn, a primary feedstock for bioethanol production in the United States, can fluctuate depending on weather conditions and market demand, affecting the profitability of bioethanol production. Similarly, weather conditions change from place to place so as the primary feedstock and associated cost. Furthermore, the conversion of feedstocks into biofuels can require significant energy input [4], with some estimates suggesting that the energy required to produce bioethanol and biodiesel can be higher than the energy contained in the final product. Additionally, the potential environmental impacts of biofuels production, including land-use change, deforestation, and greenhouse gas emissions. Finally, the commercial viability of biofuels is affected by government policies and market factors. Policy support and incentives have played a crucial role in the growth of the biofuels industry. Biomethane generation using anaerobic digestion requires significantly less energy and also generates less GHG. Net GHG emission from hydrothermal liquefaction and transesterification is reported to be −44 to 35 and −75 to −10 [5]. Due to its low net energy ratio (0.71) and GHG emissions [60.84 g CO_2-equivalent (MJ biogas)$^{-1}$], anaerobic digestion systems with hydrothermal pretreatment are more sustainable and industrially feasible [5].

5 Conclusions and ways forwards

Algae consortia in natural water bodies are very differential, the composition can vary from time to time, so their most effective utilization way is full of uncertainty. Optimization of their harvest has a high importance both on cost efficiency and on maintaining the living condition of the water body. Available literature reflects algae is emerging as a promising source of green energy and a key component of the circular economy. It can be used to produce marketable products such as biofuels, pharmaceuticals, and food supplements. These products are not only beneficial for the environment but also have the potential to become future fuels. Although production processes of these products also require energy input, which is also a challenge. For instance, bioethanol and biodiesel requires ample energy input which make the conversion not very economic feasible. Algae can be grown anywhere, even in places with limited resources such as deserts or saltwater ponds. This makes them an ideal choice for countries that lack access to traditional sources of energy like oil and gas. Due to urbanization algal blooms are emerging as a problem which can also be used for bioenergy production, GHG mitigation and secondary uses. Furthermore, algae are easy to cultivate and require fewer resources than other forms of green energy production. These facts enable to use them as an attractive option for businesses looking to reduce their carbon footprint while still producing a marketable product. Algae has become increasingly important as a tool for greenhouse gas mitigation. Algae can absorb carbon dioxide and convert it into oxygen, therefore helps in reducing the amount of carbon dioxide emissions in the atmosphere. Additionally, algae can be used to produce biofuels, which can replace traditional fossil fuels and help reduce emissions from transportation. As such, waste algae have a wide range of potential uses that could help reduce greenhouse gas emissions from water bodies. Main limitations of the study is the high and uncontrolled variability of native algae consortia, strongly depending on location and water quality, which highly influences and limits the way of utilization. Regarding future directions, improvements in harvesting technologies can play a decisive role in reducing the unit cost of native algae. Besides, we would like to highlight the importance of algae-based biogas not only in energy production, but also in electricity storage. By combining algae with solar panels, the efficiency of biogas-fired power-to-gas systems can be highly increased. The power-to-gas process allows for the recovery of CO_2 in biogas (which is worthless for cogeneration) and the storage of electricity, which can reduce the load on the national electricity network and allow for more widespread use of weather-dependent renewable energy sources (solar, wind).

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