TITLE: "ROLE OF ALGAE IN ENVIRONMENTAL SUSTAINABILITY- AN ASSESSMENT"

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Abstract

Algae are a diverse group of photosynthetic organisms containing chlorophyll, carotenoids and Phycobilins, inhabits a wide range of aquatic environments like marine, brackish and freshwater. It is also one of the planet's primary producers. Algae are classified into seven major groups such as Cyanophyceae, Chlorophyceae, Xanthophyceae, Bacillariophyceae, Chrysophyceae, Phaeophyceae and Rhodophyceae based on their pigmentation, cell structure, and storage products. They play a crucial ecological role by producing oxygen, absorbing excess carbon dioxide and forming the base of aquatic food chains. Apart from their ecological importance, algae have significant economic value. They are used in the production of biofuels, fertilizers, cosmetics, pharmaceuticals and food products like single cell protein, agar and carrageenan. The growing interest in sustainable and renewable resources have made significant increase in algal research, offering a propitious solution to environmental and energy challenges. Algae has been developed into a sustainable and adaptable resource that can help with several global issues like resource depletion, environmental degradation, food security, climate change and energy security. Chlorella, Botryococcus and Spirulina demonstrated exceptional efficiency in biomass production, carbon sequestration, nutrient recycling and bioenergy generation. In agriculture, macroalgae are primarily used as biostimulants, biofertilizers and biopesticides to improve crop growth, enhance soil health and increase plant resistance to stress. Asparagopsis taxiformis, macroalgae has significantly reduced enteric methane emissions in livestock, highlighting their utility in climate-smart farming. It proponents for targeted research into sustainable development, cost reduction, process refinement and harmonized policy frameworks to unlock algae's full potential. Inspite of these advancements, the flexibility and sustainability of algal technologies remain constrained by high production costs, energy metabolism, contamination risks and regulatory constraints—principally in food and feed sectors. Algae can become central to sustainable development in long

term environmental policy, enabling effective transitions toward cleaner energy, vibrant ecosystems and robust agricultural systems if it addresses these challenges.

.**Keywords**

Algae, bioindicator, sustainable, water quality, pollution, biofuel

1. Introduction

Environmental sustainability refers to the optimization and regulation of the natural resources for the present and future generations. The Surging population and unscrupulous development globally have led to the exhaustion of nature and its vast resources if it is unchecked it might threatens the very existence of the earth. It is in this direction the phycology (Algae)aimed research and related fields have shown a promising result towards green transformation and the preservation of the resources leading to sustainable environment. This is in line with UN resolution on sustainability goal (2030).

Algae are the members of predominantly aquatic photosynthetic plants which are both macro and microscopic. The plant body in algae is called thallus which lacks true root, stem and leaf, but they contain chlorophyll and other pigments that enable them to perform photosynthesis. Algae are considered foundation to earth's ecosystems, providing energy and organic matter to maintain ecological balance and biodiversity. The primary constituents of algae include proteins, lipids, carbohydrates, cellulose, vitamins, minerals, as well as specific compounds like algal poly-saccharides and pigments [1]. The composition may vary among different species of algae. Lipids, carbohydrates, and proteins serve as the main building blocks of algal biomass and form the basis for its conversion into food, cosmetics, pharmaceuticals and biofuels [22].

Algae trap ten times more sunlight than other photosynthetic terrestrial organisms, making them primary and significant organic producers in aquatic food chains [25]. Algae are classified into seven major groups based on their pigmentation, cell structure, and storage products. The different variety of pigments in algae enable them to perform effective photo-synthesis at different depts in aquatic environments. These pigments vary significantly across algal classes. Algae apart from their economic value, also play a crucial ecological role by absorbing carbon dioxide and producing oxygen during photosynthesis.

1.1 Algae and environmental sustainability

In the perspective of environmental sustainability, algae furnish multiple ecological and economic benefits. The escalating global sustainability challenges—ranging from climate change, food insecurity, environmental pollution and energy crises—demand innovative, eco-friendly and resource-efficient solutions. Algae, owing to their rapid growth, diverse metabolic capabilities and capacity for bioremediation, biofuel production and carbon sequestration, have emerged as promising candidates in the quest for sustainable alternatives[2]. Recent reviews underscore the potential of microalgae and macroalgae in various domains, including wastewater treatment [23], bioenergy generation [6], nutraceutical production [5] and carbon capture technologies [10].

Figure 1. Potential application of microalgae in various fields (Hoang et al., 2022).

Mankind can progress to cleaner and resilient planet by amalgamating algae into sustainable technologies and environmental impact analysis. Their versatility and natural efficiency make them a potential asset for conservation of natural resources and supporting global ecosystem vitality.

2. Method: Algae and Environmental Sustainability

Multiple approaches are practiced to explore and exploit algae for promoting environ-mental sustainability, which focus on efficient algal cultivation and Harvesting. This can be elaborated for their use in pollution control and converting algal biomass into sustainable products.

2.1 Algae Cultivation Methods: Algae cultivation is the process of growing algae for various commercial and environmental purposes. It is mainly cultivated by two methods.

Open Pond Systems: Algae are grown in shallow, open ponds and raceway systems exposed to natural sunlight. This is a cost-effective method suitable for large-scale production, especially for species tolerant to outdoor conditions.

Photobioreactors (PBRs): These are closed systems which prevent contamination and provide precise control over algal growth conditions like light, temperature and nutrients.

2.2 Harvesting of Algal Biomass: Harvesting algal biomass involves separating algae from the water to concentrate the biomass, primarily using methods like flocculation, filtration, centrifugation and flotation.

Flocculation methods: Flocculation is a process of combining algal cells into large clumps by using chemical or biological flocculants. They settle quicker and are simpler to separate.

Filtration: A physical barrier like a membrane is used to separate algae from the water.

Centrifugation– Centrifugation utilizes rapid spinning at high speeds to quickly separate algal cells by density. It is very efficient and appropriate for high-value products but energy-intensive and expensive for mass production.

Froth flotation– Froth flotation involves the use of air bubbles to float algal cells to the surface where they can be skimmed. Froth flotation works well with some buoyant species and is usually used with chemical aids to enhance efficiency. The harvested algae is employed for sustainability and commercial uses.

3. Assessment of Algae for Environmental Sustainability:

3.1 Algae as Pollution Indicator:

The rapid growth and short life cycle of algae make them the best indicator of water quality and productivity of aquatic ecosystem. Globally algae has been used as one of the important parameter to evaluate water quality of different water bodies. Tripathy et al.[28] recorded the phytoplanktons that indicated the water pollution of Ganga river of Varanasi[18], stated that phytoplankton could be used as indicator to explore the physico-chemical status of any water body. Diatoms have been utilized broadly in water quality checking [24]. Algae is noted as bioindicator of organic contaminants in twenty lakes of Karnataka [14].

Spirulina species can be used as sign of sewage pollution [4]. Seven pollution conforming phytoplankton were reported in the study on Ghuma Lake in Ahmedabad[15]. Several genera of pollution-indicator phytoplanktons belonging to Chlorophyceae, Bacilloariophycea, Myxophyceae were recorded in Gomti river, Lucknow, (India)[27]. This indicates that the algal assessment can be used as important scientific tool to visualize the degree of pollution level in water bodies.

3.2 Algae in Bioremediation of Pesticide:

Pesticides that change the actions of soil microbes will have an adverse impact on soil nutritious properties which can have serious environmental consequences. Bioremediation can be a viable, cost-effective and dependable option for pesticide contamination. Microalgae are a naturally appearing biotic agent that has been highlighted as one of the furthermost effective pollution control practices for removing pesticide impurities from agricultural runoff and polluted or contaminate water sewages. Polychlorobiphenyls one of the important component of pesticides and the worst pollutants getting absorbed by live algal cells in dissolved form was observed[13]. Thus, Algae can be effectively used as sustainable appliance in remediation approaches of pesticides toxins by their bioaccumulation, biodegradation and biosorption properties.

3.3 Algal Biofuel and Sustainable Energy:

Algal biomass energy is the most viable and right alternative to bio fossil fuels contributing to complete the energy demand supply gap of global population. Microalgae biofuels belong to the third generation type of biofuels, which are considered as an alternative energy source for fossil fuels without the disadvantages associated with the first and the second generation biofuels. Biofuel fabrication from marine algae biomass resources might serve as a viable solution in addition to an option for long-term climate change mitigation and energy [7]. The crude oil derived from marine algae (macro and microalgae) is capable of being used to make biodiesel, as well as the leftover biomasses acquired are high in carbohydrate quantity and can be employed to make bioethanol[14]. Algal Biomass has been harnessed for sustainable energy. Algae because of their rapid growth with limited resource can easily be exploited for Biofuel production which is nonhazardous and highly recyclable. Algae seems to be the most appropriate to replace or supplement the global bio fossil fuel for sustainable development.

3.4 Algae in Phycoremediation of waste water:

Phycoremediation is the use of microalgae to eliminate toxic chemicals and other contaminants from wastewater or carbon dioxide from the air altogether with biomass production. PTEs bioremediation using macro- or micro-algae has been reported through phycoremediation, such as lead by *Spirulina* [9] and *Enteromorpha* algae with silicates, cadmium, and copper by using dead biomass of *Sargassum inicola* [23]. Literature has highlighted microalgae's capacity to delete nutrients, metals, pharmaceutical drugs or pathogenic microbes from the medium.

3.5 Algae in Serving as Feed:

Algae serve as a valuable feedstock for both the food and energy industries due to their rapid growth, high lipid content and ability to absorb CO2. Researchers on many algae have confirmed the nutritional profile of algae, packed with essential human dietary supplements such as vitamins, amino acids, proteins, lipids, polyunsaturated fatty acids, carbohydrates and antioxidants. Globally seaweed is being used as one of the important feed for cattle. The Japanese fish farming industry is using spirulina genus as a chief feed as it contains 60 to 70% protein. The microalgae is not only used as nutrient supply but also as important source of bioactive compounds to improve immune response and stimulate probiotic colonization [4].

3.6 Algae in Carbon Dioxide (CO_2) Sequestration

Algae absorb CO_2 during photosynthesis, making them effective in capturing carbon from industrial emissions. Fuel gases from factories can be directed into algal cultures, reducing greenhouse gas concentrations while promoting biomass growth. Chlorella, Nannochloropsis, Botryococcus and Spirulina demonstrate exceptional efficiency in biomass production, carbon sequestration, nutrient recycling, and bioenergy generation. The efficiency of microalgae in capturing and sequestering carbon is 10 to 50 times higher than that of terrestrial plants[3]. As a result, the use of microalgae for the capture and sequestration of carbon could have significant advantages over other methods of carbon capture and sequestration technologies.

3.7 Algae as Biofertilizers

Algae are used in biofertilizers to improve soil health, increase crop yields and reduce the need for chemical fertilizers. They act as a natural, renewable source of nutrients like nitrogen, phosphorus, potassium, improve soil structure, water retention and prevents soil erosion. Algae also contain growth hormones and other beneficial metabolites. Enhancement in plant growth and floral production was reported by using *Acutodesmus dimorphus* as biofertilizer[20].

The application of algae in environmental sustainability—such as in biofuel production, wastewater treatment, carbon capture, and bioproduct manufacturing has many benefits. However, there are also disadvantages and limitations which has to be considered.

4. Disadvantages and Constraints

4.1 Algae cultivation and biodiversity impediment

The Microalgae and macroalgae comprise a highly diverse group of photosynthetic organisms, numbering between 200,000 to millions of species [21]. While extremophile strains offer cultivation advantages in harsh environments, most algae strains remain under-characterized and regulatory frameworks permit industrial use of only a few, creating bottlenecks in innovation and scale-up [21].

4.2 Impact on environment and resources

Algal cultivation is resource-intensive, especially in terms of water, nutrients, and energy. Energy inputs for photobioreactors further reduce their environmental benefit, with eutrophication and harmful algal blooms also posing risks if cultivation systems fail [27].

4.3 Economic and technological Limitations:

High costs associated with harvesting, cultivation systems, and growth media limit algae’s commercial viability. The disparity between research motivation and real world economic constraints slows adoption in energy and technology.

4.4 Public and Policy obstacles

There are concerns among the public on ecological risks such as harmful blooms and stakeholders advocate transparent communication regarding GE benefits and risks and robust environmental risk assessments [8]. Genuine public and policy confidence is needed for investment in technology.

4.5 Financial gap

Algae biotechnology lacks harmonized regulation across regions. Incentives like carbon credits, renewable fuel subsidies, or wastewater treatment offsets are either inadequate or poorly enforced [18]. Inconsistent subsidy discourages private investment and algae startups face high capital expenditures without clear long-term policy guarantees.

4.6 Genetic engineering and strain optimization

Modern CRISPR-based gene editing tools offer the potential to improve yield, lipid productivity and stress tolerance in algae. Lack of public trust and international consensus on bioengineered strains, breakthroughs in strain optimization may remain underutilized [11].

4.7 Limitations of algal residues

The improper management of algal residues may pose environmental risks if they carry heavy metals or pathogens from wastewater-grown algae. Strategies for composting, anaerobic digestion or bioplastics production from algal waste are under development but not yet widely adopted [17].

5. Conclusion

Algae are the most versatile organism with immense potential to address some of the most pressing environmental challenges, including climate change, pollution and resource depletion. The extensive use of algae in agriculture, energy and environmental management greatly aid in the accomplishment of the Sustainable Development Goals (SDGs) of the UN. Their ability to sequester carbon, remediate wastewater and serve as a sustainable feedstock for biofuels and bioplastics highlights their central role in the transition to a circular bioeconomy. Ongoing investigation and technological innovation can further refine the process, integrating algae as a core component of sustainable environmental management. However, despite these promising developments, several key challenges continue to hinder the large-scale deployment and

sustainability of algae-based technologies. High operational costs, especially those related to cultivation, harvesting, drying and potential environmental risks remain a major obstacle.
Economic viability is the primary barrier to the large-scale industrial adoption of algae-based CCUS (Carbon Capture, Utilization, and Storage). The successful integration of algae into mainstream sustainable practices requires overcoming significant technological and economic hurdles to make large-scale cultivation both cost-effective and environmentally sound.

Besides, integrating algal systems into broader industrial symbiosis models like those involving agricultural and municipal waste could increase efficiency and reduce costs. Regulatory reform and harmonization is very important to support commercialization, initiatives to improve public awareness and acceptance of algae-based products in food and agriculture. Addressing these issues will be essential for expressing algae's full potential as a cornerstone of sustainable development.

6. References

1. Babich, O.; Sukhikh, S.; Larina, V.; Kalashnikova, O.; Kashirskikh, E.; Prosekov, A.; Noskova, S.; Ivanova, S.; Fendri, I.; Smaoui, S.; et al (2022). Algae: Study of Edible and Biologically Active Fractions, Their Properties and applications. *Plants* , *11*, 780. [**Google Scholar**] [**CrossRef**]

2. Bishnu Dev Das and Ajaya Bhattarai (2025). The versatility of algae in addressing the global sustainability challenges. front Bioeng Biotechnol. 1;13:1621817. doi: 10.3389/fbioe.2025.1621817

3. Bhola, V. , Swalaha, F., Ranjith Kumar, R., Singh, M., Bux, F.J.I.J.o.E.S. (2014) Overview of the potential of microalgae for CO2 sequestration Technology, 11 (7), pp. 2103-2118. View at publisherCrossrefView in ScopusGoogle Scholar

4. Bhosale LJ, Patil SM, Dhumal SN, SatheSS (2010) Occurrence of phytoplankton in the water bodies of Miraj Tahasil of Maharashtra. The Ecoscan4 : 73-76.

5. Bleakley S., Hayes M. (2017). Algal proteins: extraction, application, and challenges concerning production. Foods 6 (5), 33. 10.3390/foods6050033 [DOI] [PMC free article] [PubMed] [Google Scholar]
6. Borowitzka M., Moheimani N. (2013). "Sustainable biofuels from algae,"Mitig. Adapt. Strategies Glob. Change, 18, 13–25. 10.1007/s11027-010-9271-9 [DOI] [Google Scholar]

7. Brennan L., Owende P. (2010). Biofuels from microalgae—A review of technologies for production, processing, and extractions of biofuels and co-products. Renew. Sustain. Energy Rev. 14 (2), 557–577. 10.1016/j.rser.2009.10.009 [DOI] [Google Scholar]

8. Calatrava V., Gonzalez-Ballester D., Dubini A. (2024). Microalgae for bioremediation: advances, challenges, and public perception on genetic engineering. BMC Plant Biol. 24, 1261. 10.1186/s12870-024-05995-5 [DOI] [PMC free article] [PubMed] [Google Scholar]
9. Chen, H., Pan, SS. (2005). Bioremediation potential of spirulina: toxicity and biosorption studies of lead. *J Zheijang Univ Sci B* **6**, 171–174. https://doi.org/10.1631/jzus.2005.B0171
10. Chisti, Y. (2007). Biodiesel from microalgae. *Biotechnol. Adv.* 25 (3), 294–306. doi:10.1016/j.biotechadv.2007.02.001. PubMed Abstract | CrossRef Full Text | Google Scholar.
11. Dhokane D., Shaikh A., Yadav A., Giri N., Bandyopadhyay A., Dasgupta S., et al. (2023). CRISPR-based bioengineering in microalgae for production of industrially important biomolecules. Front. Bioeng. Biotechnol. 11, 1267826. 10.3389/fbioe.2023.1267826 [DOI] [PMC free article] [PubMed] [Google Scholar.
12. Duarte, S. Hernández, A. Ibañez, A. Canto. (2018). Macroalgae as Soil Conditioners or Growth Promoters of Pisum sativum 13 . (L)Annu. Res. Rev. Biol., 27 , pp. 1-8 10.9734/arrb/2018/43272.
13. Fitzgerald SA, Steuer JJ (2006). Association of polychlorinated biphenyls (PCBs) with live algae and total lipids in rivers-a field-based approach. Sci Total Environ. 354:60-74
14. Hoang, A. T., Sirohi, R., Pandey, A., Nižetić, S., Lam, S. S., Chen, W.-H., et al. (2022). Biofuel production from microalgae: challenges and chances. *Phytochem. Rev.* 22 (4), 1089–1126. doi:10.1007/s11101-022-09819-y CrossRef Full Text | Google Scholar
15. Hosmani Shankar P (2013) Fresh Water Algae as Indicators of Water Quality. Universal Journal of Environmental Research & Technology 3 : 473-482 . Cross Ref Full Text | Google Scholar.
16. KotadiyaNG, MuliaNR (2014)Phytoplankton Diversity, Density and Palmer's Pollution Index of Freshwater Lake, KotadiyaNG, MuliaNR (2014)Phytoplankton Diversity, Density and Palmer's Pollution Index of Freshwater Lake, Rural Area of Ahmedabad. International Global Journal for Research Analysis 3.
17. Lopez-Tenllado F. J., Motta I. L., Hill J. M. (2021). Modification of biochar with high-energy ball milling: development of porosity and surface acid functional groups. Bioresour. Technol. Rep. 15, 100704. 10.1016/j.biteb.2021.100704 [DOI] [Google Scholar]
18. Moshood T. D., Nawanir G., Mahmud F. (2021). Microalgae biofuels production: a systematic review on socioeconomic prospects of microalgae biofuels and policy implications. Environ. Challenges 5, 100207. 10.1016/j.envc.2021.100207 [DOI] [Google Scholar]
19. MattaG, Pandey RR, Saini KK (2015) Assessment of pollution on water quality and phytoplankton diversity in canal system of River Ganga. World Journal of Pharmaceutical Research 4 : 889-908.
20. Nosheen S, Ajmal I, Song Y (2021) Microbes as Biofertilizers, a Potential Approach for Sustainable Crop Production. Sustain 2021, Vol 13, Page 1868 13:1868. https://doi.org/10.3390/SU13041868.Google Scholar
21. Occhipinti, P. S., Russo, N., Foti, P., Zingale, I. M., Pino, A., Romeo, F. V., et al. (2023). Current challenges of microalgae applications: exploiting the potential of non-conventional microalgae species. *J. Sci. Food Agric.* 104 (7), 3823–3833. doi:10.1002/jsfa.13136
PubMed Abstract | CrossRef Full Text | Google Scholar

22. Özçimen, D.; Koçer, A.T.; İnan, B.; Özer, T. (2020). Bioethanol Production from Microalgae. In *Handbook of Microalgae-Based Processes and Products*; Academic Press: Cambridge, MA, USA,; pp. 373–389. [Google Scholar] [CrossRef].
23. M. Patrón-Prado, B. Acosta-Vargas, E. Serviere-Zaragoza, L.C. Méndez-Rodríguez (2010). Copper and cadmium biosorption by dried seaweed Sargassum sinicola in saline wastewater. Water Air Soil Pollut, 210 (1-4), pp. 197-202

24. Rawat, I., Ranjith Kumar, R., Mutanda, T., and Bux, F. (2011). Dual role of microalgae: Phycoremediation of domestic wastewater and biomass production for sustainable biofuels production. *Appl. Energy* 88 (10), 3411–3424. doi:10.1016/j.apenergy.2010.11.025 CrossRef Full Text | Google Scholar
25. Round F.E (1991) Diatoms in river water-monitoring studies. Journal of applied phycology3 : 129-145.
26. Sahu, A.K., Mir, S. Nayak, B. Baitharu I.(2024) Sustainable management of eutrophication and problems associated with the algal toxin in ponds and lakes of rural areas. In Water Resources Management for Rural development, Elsevier, pp. 155-170.

27. Schischke A., Papenfuß P., Brem M., Kurz P., Rathgeber A. W. (2023). Sustainable energy transition and its demand for scarce resources: insights into the German energiewende through a new risk assessment framework. Renew. Sustain. Energy Rev. 176, 113190. 10.1016/j.rser.2023.113190 [DOI] [Google Scholar]
28. Singh P. (2015) A seasonal study of phytoplanktons diversity of Gomti river Lucknow,(UP) India: A pollution indicator. IJREAS 5 : 43-48.
29. Tripathi BD, ShuklaSC,Kant R (1989) Ecological. investigation on physio- chemical characteristics and phytoplankton productivity of river Ganga at Varanasi. Geobios 16 : 20-27.