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Microalgae as environmental helpers: A comprehensive review on their role in climate mitigation, ocean health, and ecosystem restoration

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Abstract

Microalgae are the indispensable components of different ecosystems, ranging from marine and freshwater to terrestrial environments. These tiny organisms contribute a lot to ecological stability, nutrient cycling, and biogeochemical processes. Their potential contribution to environmental sustainability has increasingly been realized, and hence microalgae are now being explored for various applications in climate change mitigation, water quality improvement, and ecosystem restoration. The review hereafter tries to assess in some detail the multiple environmental services of microalgae, with a focus on carbon sequestration, ocean acidification buffering, nutrient recycling, and ecosystem restoration. It focuses on the local uses of microalgae for enhancing coastal and marine ecosystems health, with a focus on sensitive areas. Microalgae have a very important role in the fight against climate change since they can capture atmospheric CO_2, which is functional in the correct running of the carbon cycle. They also contribute to the betterment of water quality by serving as natural biofilters, absorbing excess nutrients and contaminants. Their contribution to aquatic food webs and habitat creation is vital in terms of maintaining biodiversity. In the process of ecosystem restoration, microalgae play a vital role in the rehabilitation of degraded marine, coastal, and terrestrial habitats by stabilizing sediments, enhancing nutrient availability, and supporting ecological resilience. Considering their impressive adaptation and sustainability features, microalgae can form a potentially attractive opportunity for inclusion into global and regional environmental management regimes. More precisely, the involvement of microalgae in conservation endeavors will contribute substantially to water quality improvement, marine biodiversity maintenance, and mitigation of climate change impacts in areas like the coastal districts of Andhra Pradesh, India. Further research and technology development in various microalgal technologies offer the potential not only to provide solutions to global climate change but can also be used to confront local ecological nuisances.

Key words: Extraction of Micro Algal; Ocean Acidity; Climatic Change; Studies of Micro Algae In East; West Coastal Line In A.P (Cover Chirala; Nellore; Machilipatnam)

1. Introduction

Microalgae are small, yet vital and often forgotten, constituents of marine, freshwater, and terrestrial ecosystems. These microscopic organisms have a wide array of critical ecological roles that are central in maintaining ecosystem health and supporting global biogeochemical cycles. Among their most vital roles, they have the ability to photosynthesize.

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They use sunlight to convert CO_2 into organic matter, a process providing a primary source of energy in various ecosystems. In aquatic environments, it is estimated that 50% of Earth's oxygen is produced by phytoplankton, mostly microalgae, making them one of the largest contributors to the global oxygen supply (1). Their photosynthetic activity is also directly involved in the global carbon cycle, where they fix large amounts of atmospheric CO_2. The fixation of this carbon helps in the regulation of the concentration of CO_2 in the atmosphere, therefore reducing the greenhouse effect and helping to counteract climate change.(2). Hence, the microalgae behave like a natural sink for carbon: they absorb the atmospheric CO_2 and convert it into biomass that eventually gets transferred either to the deep ocean waters or gets buried in sediments.(3)

Sequestration of carbon by microalgae has an important implication for global warming, considering it is one of the very few natural mechanisms that exist to help diminish the escalating levels of CO_2 in the atmosphere. Recent various research has pointed to the fact that the use of marine algae biomass for biofuel purposes amplifies the role they may play in carbon mitigation, taking the place of fossil fuels with renewable energy and increasing global carbon management (2). Microalgae are components of the carbon cycle themselves; they do not only take up CO_2 but also serve to store more carbon in their aquatic ecosystems. When these microorganisms are consumed by herbivores or decomposed by bacteria, much of the carbon is transported into deeper layers of the ocean, where it stays sequestered for long periods. That acts to regularize Earth's climate by enhancing the capacity of the oceans to act as a carbon sink (3)(4). Moreover, developments related to carbon capture using algae have shown promising results in industry and provided scalable solutions for effective CO_2 sequestration (5).

While various regional approaches have made similar natural processes address the environmental imperatives worldwide, in recent times, particularly in Andhra Pradesh, there are initiations that stipulate these ecological roles in response to environmental issues at large. Therefore, the Andhra Pradesh policy for Integrated Clean Energy, 2024, "proposes bringing down the projected emissions of carbon in 2030 by 2.5 to 3.0 billion tons through additional sinks created by higher forest and tree cover." Aside from this US. USAID, Vignan's Foundation launch a tree nursery at Vadlamudi in Guntur district of Andhra Pradesh. The new nursery would scale up the production of plants to capture carbon for mitigating climate change at the local and national levels and increase the potential of the State as a carbon sink. This also aligns with a greater awareness of how carbon sinks-natural features like microalgae and forests-are contributing to sequestering CO_2, acting to temper the greenhouse effect. With these improvements in natural and policy-driven carbon sequestration, Andhra Pradesh contributes to global efforts for counteracting climate change.

Besides their role in carbon cycling, microalgae are also important in nutrient cycling, especially in both marine and freshwater environments. These organisms absorb essential nutrients such as nitrogen and phosphorus, which are integral for plant growth. In doing so, they help maintain a balance of nutrients in water bodies, which is crucial for ecosystem health (6).Eutrophication is a process where excess nutrients, mainly from agricultural runoff, sewage, and industrial wastes, favor algal blooms growth, deplete the oxygen, and acidify water, eventually causing an aquatic ecosystem to collapse. Active microalgae mitigate eutrophication by taking up excess nitrogen and phosphorus, preventing HABs and maintaining the healthy nutrient balance in aquatic systems (7). By regulating nutrient concentrations, microalgae do not only prevent hypoxic conditions but also enhance water quality supporting the sustainability of marine and freshwater ecosystems.(6).

Currently, the world is faced with various environmental challenges that put the stability of ecosystems and biodiversity at risk. Climate change has been a critical issue lately due to increasing global temperatures, altered weather conditions, and shifting ocean circulation-these being promoted by increased levels of greenhouse gases, mainly carbon dioxide (CO_2), in the atmosphere. The changes in climate do not only affect Earth's climate but also have a ripple effect on marine and terrestrial ecosystems. In marine environments, ocean warming, in combination with ocean acidification, is placing enormous stress on ecosystems, which are thereby more susceptible to biodiversity loss and changes in ecosystem services (8). The repercussions of these environmental disruptions are far-reaching and threaten the delicate balance that sustains life on Earth. Microalgae are extremely important in such a context and, more so, in mitigation, especially by their carbon-sequestering capabilities in aquatic and terrestrial ecosystems.(9)

Microalgae are necessary in the atmospheric reduction of CO_2 by means of carbon sequestration in which they convert it into organic biomass through photosynthesis. This supports the reduction in speed of climate alteration and provides one way of natural stabilization to the global carbon cycle. Regarding aquatic ecosystems, microalgae, in general, contribute to the removal of CO_2 by acting as a carbon sink. While carrying out photosynthesis, they fix carbon and build biomass that may be exported into deeper waters or buried in sediments, thereby removing it from the atmosphere and reducing the greenhouse effect (3). This natural form of carbon capture, in which all phytoplankton engage, is crucial as the world looks for ways to meet the rising challenges of global warming and presents a sustainable pathway toward reducing levels of atmospheric CO_2 (10).

Eutrophication is another major environmental challenge caused mainly by the discharge of excess nutrients through agricultural runoff, industrial waste, and sewage, including nitrogen and phosphorus, which spur a rapid growth of algae in bodies of water. This algal bloom caused by these nutrients leads to an oxygen deficit in the water due to their respiration, thus giving rise to hypoxic conditions or zones of low oxygen levels where most marine life cannot survive (Carpenter et al., 1998). While excess nutrients due to human activities are feeding the HABs, microalgae could act as natural biofilters and mitigate the eutrophication effects. Microalgae, in this respect, reestablish the nutritional balance in the aquatic ecosystem through the removal of excess nitrogen and phosphorus, thereby preventing or lessening the severity of eutrophication. In such a manner, this process has also been participating in general improvement of water quality for sustainability of aquatic environments and the organisms dependent on them.(12)(13).

More and more, ecosystem degradation, deforestation, habitat loss, and over exploitation of resources have all become factors that add to the increasing loss of biodiversity throughout the world. Such disruption in food webs and destruction of habitats affects the survival of wildlife dependent on these very same environments. A common organism in each ecosystem, Microalgae holds one very important position wherein biodiversity is definitely involved concerning complex food networks and other imperative resources regarding oxygen production and nutrient cycling among others. Most importantly, on point, is it provides a base for habitat creating. (14) state that the decay of micro-algae due to pollution, Climatic Shift or their habitats being disturbed may lead the entire ecosystem of an area up an negative spiral, a chain reaction till its collapse entirely occurs. Thus, restoration and conservation of microalgal populations are very important for the maintenance of biodiversity and healthy status. The role of microalgae in food webs and ecosystem stability is so crucial that recovery of their assemblages must be included in all future strategies that are designed to combat biodiversity loss and preserve ecosystem integrity worldwide.(15)

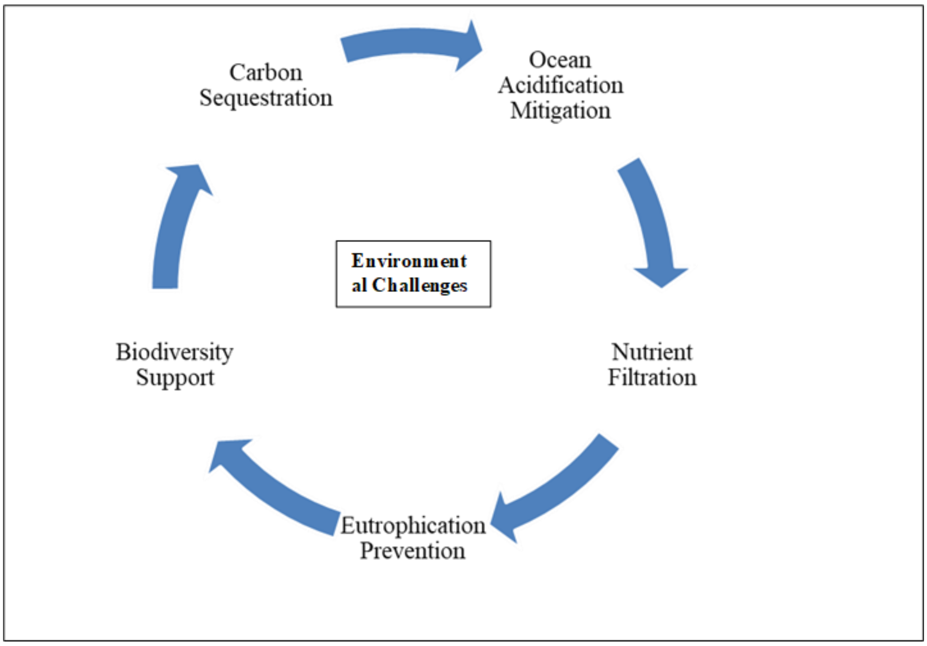

Figure 1 Environmental Challenges

1.1. Overview of Microalgae as Environmental Helpers

Not only are microalgae critical for the proper functioning of aquatic ecosystems, but they also provide a wide range of valuable services that contribute to environmental sustainability in various contexts. With their multi-faceted roles in climate change mitigation, water quality improvement, ecosystem restoration, and even agriculture, they have come to be regarded as important contributors in global efforts to resolve some of the most critical environmental issues. Probably the most important contribution of microalgae is their ability to absorb and fix atmospheric carbon dioxide through photosynthesis into organic matter. This carbon sequestration can be an important natural mechanism in climate change mitigation because it reduces the concentration of CO2, a greenhouse gas, in the atmosphere. In this sense, microalgae represent an excellent way of countering global warming, given the transformation of excess CO_2 into biomass. Microalgae-based systems for carbon capture are in high demand because of their sustainability while trying to fight growing CO_2 levels. These algae-based technologies provide environmentally friendly and cost-effective alternatives to the conventional methods of carbon capture with added benefits of value byproducts, such as biofuels, to help support both climate change mitigation and the development of green energy sources.(16)(17).

Besides the role of microalgae in climate change mitigation, there has been considerable interest in this group of organisms for their promise as a source of biofuels. Certain species of microalgae have high lipid content and rapid growth rates, making them ideal candidates for biofuel production. Biofuels derived from algae, such as biodiesel, bioethanol, and biogas, are some of the available viable alternatives to fossil fuels. It helps reduce dependence on non-renewable energy sources and mitigates environmental impacts associated with extraction and use. Microalgae have emerged as one of the renewable viable alternatives for addressing future energy needs in view of increasing concerns about the depletion of fossil fuels and pollution caused by their combustion (18). Further integration of algae-based biofuels into the energy world market could result in a marked decrease in greenhouse gas emissions and a faster transition toward greener, cleaner, and more renewable sources of energy.(19).

Microalgae will also provide equally promising solutions for water pollution issues, especially in the process of bioremediation. Algae-based waste water treatment has emerged in recent decades as an efficient method of removing common pollutants like nitrogen, phosphorus, and heavy metals economically and in tune with ecological imperatives. A number of technologies traditionally used today for waste water treatment basically involve chemical means, which considerably harm the environment, whereas methods using algae function more in concurrence with nature. Assimilation of excessive nutrients and pollutants by algae is a natural way, which helps in water purification, reducing eutrophication and generally improving water quality. Some species of microalgae, such as *Chlorella*, *Spirulina*, and *Scenedesmus*, have been found in different pilot studies for biofilter applications and wastewater remediation (20) (21).

Especially within the context of ecosystem restoration, microalgae have been invaluable, particularly in coastal and marine environments. Coral reefs, which are particularly badly affected by climate change, pollution, and overfishing, are now being rehabilitated using algal-based methods that are under test. The role of microalgae in coral reef ecosystems is twofold: aside from providing food and energy to corals through photosynthesis, some species of algae will also take part in the buffering of pH levels of surrounding waters, hence reducing the stress to organisms caused by ocean acidification. This buffering effect is particularly important as ocean acidification threatens the survival of calcifying organisms, including corals. By helping to restore coral reefs, microalgae contribute to the general health of marine ecosystems and increase biodiversity. (22).

2. Microalgae and Climate Change Mitigation

Microalgae have great potential in mitigating climate change by sequestering CO_2, reducing GHG emissions, buffering ocean acidification, and enhancing ecosystem resilience. Many research studies are exploring the wide usage of microalgae in climate resilience strategies, placing them as powerful allies in global efforts to stabilize the climate.

2.1. CO_2 Sequestration and Greenhouse Gas Reduction

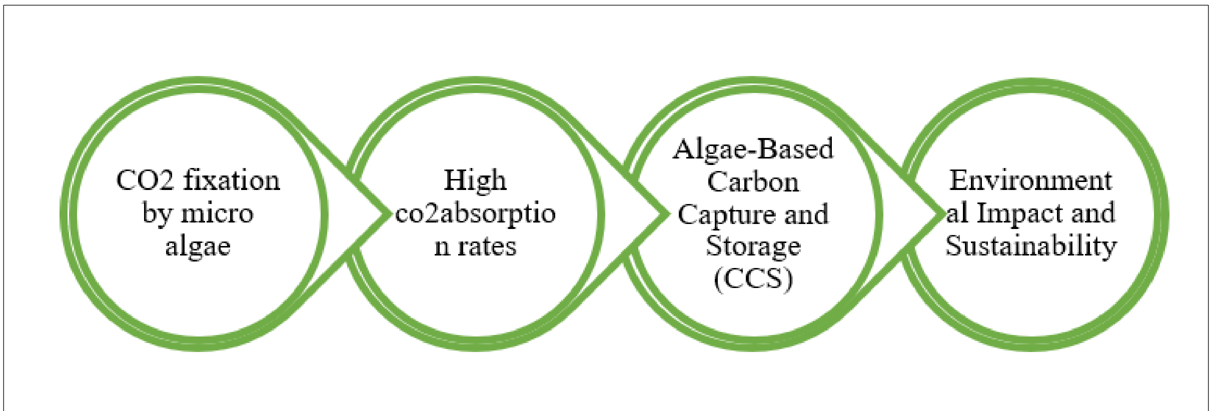

Figure 2 Microalgae and CO_2 Sequestration: A Sustainable Carbon Cycle

Microalgae have a very high effectiveness in fixing CO_2 by converting atmospheric CO_2 to organic carbon through photosynthesis. Later on, carbon is stored in the algae biomass or further transferred to the aquatic environment due to sedimentation and biomass turnover. Scientific evidence has shown that some microalgal species, like *Chlorella vulgaris* and *Spirulina platensis*, exhibit high CO_2 absorption rates, especially when cultivated under conditions with an optimized carbon uptake rate (23). Other works estimated the global CO_2 sequestration by marine microalgae, mainly phytoplankton, to range between 50% of global primary productivity (1). This includes research into innovative systems to take advantage of this potential natural CO2 sequestration, such as algae-based CCS. Algal-based CCS is a green, possibly cost-effective alternative for carbon dioxide removal. Algae in such cases would be grown in a CO2-rich atmosphere-for example, near an electrical power generation station-and thereby absorb the CO2 emitted. It can then store the carbon from CO2 in their biomass, to be subsequently processed for biofuels or other useful materials (16).

2.2. Mitigation of Ocean Acidification

Besides their potential to sequester CO_2, microalgae buffer ocean acidity, hence being of great importance to the pH value of marine ecosystems. Photosynthesis by microalgae converts the produced bicarbonate, reducing CO_2 concentration while increasing the alkalinity of surrounding waters. This reduction in CO_2 helps to stabilize the pH of the ocean, which is crucial for marine species, especially calcifying organisms like corals and shellfish that rely on stable pH to form their calcium carbonate structures (24). Several studies have indicated the role of microalgae in enhancing calcification and strengthening the resistance of coral reefs against acidification. Field studies on coral reefs, for instance, have indicated that algae may play a role in pH regulation at a local scale and hence potentially moderate the impacts of acidification on reef ecosystems, improving coral health (22).

Table 1 Overlaps and unique aspects

Theme	Global Perspective (File Content)	Regional Perspective (Updated Content)
Carbon Sequestration	Highlights the global role of microalgae in CO_2 absorption, biomass formation, and carbon storage. Discusses advancements in algae-based carbon capture technologies and biofuel production as scalable solutions.	Focuses on Andhra Pradesh's Integrated Clean Energy Policy (ICE, 2024) to enhance carbon sinks through afforestation and natural systems, including microalgae.
Climate Change Mitigation	Explores algae-based biofuel production as a sustainable energy source to reduce fossil fuel dependency globally. Mentions algae in carbon-neutralization technologies.	Highlights the localized contributions of microalgae in Andhra Pradesh, specifically in mitigating rising CO_2 levels along coastal regions.
Ocean Acidification	Explains how microalgae buffer ocean pH levels through photosynthesis, aiding calcifying organisms like corals globally. Cites global case studies of acidification mitigation.	Applies ocean acidification insights to Andhra Pradesh's coastal ecosystems, emphasizing microalgae's role in stabilizing pH and protecting marine biodiversity.
Nutrient Cycling	Discusses microalgae's role in regulating nitrogen and phosphorus globally, with examples of wastewater remediation using species like *Chlorella* and *Scenedesmus*.	Highlights Andhra Pradesh's specific nutrient challenges (agricultural runoff, sewage) and how microalgae can mitigate eutrophication in Nellore, Chirala, and Machilipatnam.
Water Quality Improvement	Focuses on microalgae's ability to act as biofilters for pollutants and nutrients, preventing harmful algal blooms and hypoxia. Discusses bioremediation of heavy metals globally.	Localizes the role of microalgae in biofiltration for nutrient pollution control and improving water quality in Andhra Pradesh's estuaries and coastal waters.
Biodiversity Support	Details microalgae's role in forming the foundation of aquatic food webs, supporting zooplankton, shellfish, and fish globally. Notes contributions to ecosystem resilience.	Highlights studies on local species diversity in Andhra Pradesh (e.g., *Chlorella* and *Spirulina*) and their role in sustaining coastal fisheries and biodiversity.
Ecosystem Restoration	Discusses applications in coral reef recovery, seagrass regeneration, and soil stabilization in degraded lands worldwide. Mentions algae's role in climate-resilient habitats.	Emphasizes restoration initiatives in Andhra Pradesh, such as using microalgae for mangrove and seagrass conservation, sediment stabilization, and habitat creation.
Regional Context	Focuses on global case studies without specific regional emphasis. Highlights broad technological and environmental applications of microalgae.	Localizes global principles to Andhra Pradesh, showcasing Chirala, Nellore, and Machilipatnam as dynamic ecosystems for microalgal integration.
Policy and Governance	Limited policy discussion. Mentions the need for global frameworks to support algae-based	Discusses Andhra Pradesh's ICE Policy and USAID-supported initiatives as practical

	technologies. Highlights research gaps and challenges in scaling up applications.	examples of integrating microalgae into regional environmental policies.

2.3. Enhancing Ecosystem Resilience to Climate Change

Microalgae in both aquatic and terrestrial ecosystems help mediate resilience towards climate change via impacts on biodiversity and ecosystem productivity. Coral reefs rely strongly on mutualistic relationships with specific forms of algae-such as of the genus Symbiodinium-they provide them with nutrients/energy through their photosynthetic activity. That mutualistic association maintains health and resilience within corals to resist stressors like ocean warming and acidification (15). Besides, microalgae help to take part in coastal defense and shoreline stabilization. Seagrass beds, which rely on the occurrence of microalgae, will impede coastal erosion by means of sediment stabilization, hence playing a crucial role in sea-level rise mitigation. Microalgae are known to have played their role in nutrient cycling and feeding plants in both salt marsh systems and mangroves, hence making these systems resilient to climate change (25). By promoting biodiversity and supporting vital habitats, microalgae are a necessary component for improving ecosystem resilience in the face of global warming.

3. Microalgae in Ocean Health and Water Quality

The involvement of microalgae in nutrient cycling, pollution mitigation, and treatment of waste water makes them very valuable for ocean health and water quality enhancement. They act as biofilters, absorbing excess nutrients and serving as the base for aquatic food webs, therefore contributing to the stability and resilience of general aquatic ecosystems.

3.1. Role in Nutrient Cycling and Pollution Reduction

Microalgae are a part of nutrient cycling, particularly in their capability to absorb and recycle nitrogen and phosphorus from aquatic environments. In nutrient-enriched waters, such as those from agricultural runoff, sewage, and industrial discharge, microalgae assimilate excess nitrogen and phosphorus, preventing nutrient overload and eutrophication (26). Eutrophication, often promoted by nutrient pollution, may result in harmful algal blooms, hypoxia, and loss of biodiversity. By absorbing the extra available nutrition, microalgae help reduce such effects and maintain the balance in the ecosystem. Some research has shown that the species of microalgae such as *Chlorella vulgaris* and *Scenedesmus obliquus* are capable of effective uptake of nitrogen and phosphorus, hence regulating nutrient availability and improving water quality in nutrient-polluted environments (6).

3.2. Wastewater Treatment Applications

Nowadays, microalgae have been increasingly used in the waste water treatment processes due to their ability to eliminate the full range of pollutants: from nitrogen and phosphorus up to heavy metals and organic compounds. Algal-based treatment systems will be more environmentally friendly and cost-effective; besides, such an approach will contribute much to the recovery of valuable nutrients from waste water. These small pilot studies gave results showing species such as *Chlorella* and *Spirulina* were effective in taking the nutrient loads off waste water so as to convert them into reuse water either for agricultural or industrial usage (20). In addition, it is reported that microalgae are efficient not only for nutrient uptake but also able to bioremediate heavy metals through binding processes inside their cellular wall and avoid heavy metals from discharging into water bodies. For instance, *Chlorella pyrenoidosa* has been found to be effective in the removal of cadmium, lead, and mercury from wastewater and as such proves promising for the treatment of industrial effluents (21). Microalgal biomass generated during wastewater treatment systems could be valorized into biofertilizers, animal feed, or biofuels, thus adopting a circular economy approach toward pollution management.

3.3. Impact on Marine Biodiversity

The ocean's biodiversity depends on microalgae because it provides the initial base in aquatic food chains. In other words, microalgae produce organic matter and oxygen through photosynthesis for other diverse marine life, such as zooplankton, small fish, and shellfish. The population of microalgae and their productivity determine how a marine food web is supposed to be in its structure and stability. Variations in microalgal populations have been found to influence the distribution, diversity, and abundance of several marine species, hence playing a critical role in the maintenance of ecosystem health (27). Habitat provision through microalgae contributes to offering food and shelter for several species regarding their survival. In coral reefs, seagrass meadows, and mangrove forests, healthy microalgal populations must be guaranteed for the maintenance of biodiversity, productivity, and resilience. Because of their importance, microalgal habitats need effective protection and consensual management worldwide in order to be able to avert degradation within marine ecosystems from causing damage to health and losses in biodiversity.

4. Microalgae in Ecosystem Restoration and Habitat Rehabilitation

Microalgae are increasingly recognized for their potential in ecosystem restoration and habitat rehabilitation across a variety of environments, from coastal and marine ecosystems to arid terrestrial landscapes. Because of their involvement in nutrient cycling, carbon sequestration, and habitat creation, microalgae provide unique opportunities to revitalize degraded habitats, support biodiversity, and promote ecosystem stability.

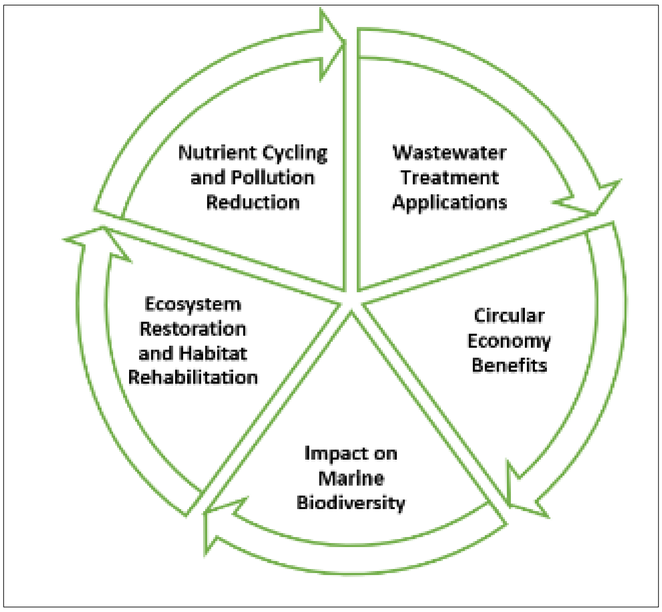

Figure 3 Microalgae in Ecosystem Restoration and Habitat Rehabilitation

4.1. Coastal and Marine Ecosystem Restoration

Among those, mangroves, seagrasses, and coral reefs supply a number of ecosystem services concerned with biodiversity, shoreline protection, and fisheries. Such ecosystems are under immense pressure from pollution, climate change, and habitat loss. Microalgae help in such ecosystem restorations through nutrient cycling, enhanced growth, and stabilization in degraded areas. In coral reefs, microalgae like *Symbiodinium* have symbiotic relationships with coral polyps, providing them with nutrients through photosynthesis, thus helping in coral health and growth (15). Algal species are also used in reef restoration projects where they buffer pH levels and create suitable conditions for coral larvae settlement, which is crucial for the recovery of coral reefs affected by bleaching events. (22)

Seagrass meadows and mangrove forests, essential for carbon storage and habitat provision, benefit from microalgae's ability to stabilize sediments and recycle nutrients. For instance, benthic microalgae contribute to sediment stabilization by forming biofilms that trap particles, helping prevent erosion and promoting seagrass regrowth. These biofilms enhance the structure and resiliece of coastal habitats, making them more resistant to climate-induced changes and supporting a diversity of marine life. (25).

4.2. Microalgae in Soil and Land Restoration

Microalgae have promising applications in soil and land restoration, especially in arid and semi-arid regions where soil degradation is prevalent. Soil degradation, often due to erosion, salinization, and nutrient loss, leads to decreased fertility and agricultural productivity. Microalgae can improve soil quality by enhancing nutrient availability and soil structure, ultimately aiding in the recovery of degraded lands. Certain algal species, like *Cyanobacteria*, are capable of nitrogen fixation, adding valuable nitrogen to the soil and increasing its fertility (21). Additionally, microalgae produce extracellular polysaccharides that help bind soil particles, reducing erosion and improving water retention. This function is particularly beneficial in arid regions, where water scarcity and soil erosion are significant challenges.

Under research for their possible application as biofertilizers are microalgae in degraded agricultural lands, since this can replace or diminish the use of chemical fertilizers. Microalgae improve soil fertility by releasing vital nutrients such as nitrogen, phosphorus, and potassium and thus contribute to sustainable agriculture. According to research, algal biofertilizers improve not only soil structure and microbial diversity but also plant growth and may thus be a promising strategy for ecological restoration of hard-to-manage landscapes (28).

4.3. Microalgae and Habitat Creation

Microalgae are also habitat providers in both aquatic and terrestrial systems due to their contribution to the development of biofilms and bio-constructs, which offer stability to systems and host many organisms. Aquatic microalgae create dense biofilms on substrates, developing into microhabitats for bacteria, invertebrates, and fish larvae. These biofilms act as nutrient-rich surfaces which attract and help support several species, adding biodiversity and supporting the first stages of aquatic food webs (6). Besides, biofilms play an important role in sediment stabilization and water filtration; therefore, they are seen to offer key ecosystem services in sensitive aquatic habitats, wetlands, and estuaries.

Above ground, microalgae play an important role in the development of substrata that provide habitats for both soil fauna and pioneer plants. In deserts or drylands, algae build a type of biocrust that stabilizes the soil and reduces erosion while enhancing water infiltration. These biocrusts play an important role in the formation of habitat in dryland ecosystems by providing a base on which other organisms may live and improve the soil conditions over time, hence enabling other plants and vegetation to grow successfully. Conversely, biocrust-forming algae contribute significantly to land rehabilitation in both desertification and degradation processes of such ecosystems during their early successional stage and contribute in the long term (29).

5. Applications of Microalgae in Sustainable Development

Nowadays, microalgae tend to act as versatile contributors to sustainable development through a number of uses regarding biofuel production, bioproducts, and agriculture. Further, such uses exploit the biological functions of microalgae for application fields that hitherto relied on traditional sources and are designed to help maintain environmental sustainability while stimulating economic development and resource security. Because of its ability to exist in different environments, the microalgae and the production of high-value substances they can accomplish put them in the forefront regarding new, viable sustainable applications.

5.1. Biofuels and Renewable Energy

Microalgae have started to emerge as a potential feedstock for the renewable production of biofuels that could help satisfy the growing demand for clean energy, with a limited dependence on fossil fuels. In comparison with conventional biomass crops, microalgae offer an incomparably high biomass yield and do not require the use of arable land for growth, avoiding direct competition with the production of foodstuffs. Biofuels produced by microalgae include biodiesel, bioethanol, and biogas, derived respectively through lipid extraction, fermentation of biomass, and anaerobic digestion of algae. Species such as *Chlorella* and *Nannochloropsis* have been proven to contain a high content of lipid and, therefore, stand out as good feedstock for the production of biodiesel (18). Being the case, algal-based biodiesel offers the added advantages of being effectively blended with the conventional diesel and used in current diesel engines, thus offering another flexible alternative to the source of fuels (16).

Apart from biodiesel, promising microalgal bioethanol and biogas production for energy sustainability also exist. Algal bioethanol includes the fermentation of carbohydrate-rich species, such as *Spirulina*, which can be grown on non-arable land with a very low input of freshwater. Production of biogas by algal biomass contributes to energy sustainability because in biogas production, the feedstocks are organic wastes, while a decrease in GHG emission and circular economy in wastes management is obtained. While there are considerable challenges to ensure that algae-derived biofuels are as productive and scalable in an economically viable manner, research continues that hopes to elevate productivity and diminished costs, enabling microalgal biofuels to figure prominently in the lineup of renewable-energy sources globally (21).

5.2. Bioproducts and Pharmaceuticals

Microalgae represent a very important source of bioactive compounds for pharmaceutical, nutraceutical, cosmetic, and animal feed applications. Various algal species contain proteins, lipids, pigments, vitamins, and antioxidants which could be extracted and applied in high value products. *Spirulina* and *Chlorella* have gained a wider acceptance in the production of nutraceuticals since they contain very high protein and essential amino acid levels, therefore being of great application as dietary supplements in health foods (29). Cosmetic uses of microalgae also include moisturizing, anti-aging, and UV protection, for which beta-carotene and astaxanthin from Haematococcus pluvialis are highly valued for their antioxidant effects (30).

In the field of pharmacy, microalgae can also be used for developing new medicines. Most of the species of algae are capable of synthesizing bioactive compounds with antimicrobial, antiviral, and anticancer activities. For instance, sulfated polysaccharides from red algae have been found to have potential antiviral activity, whereas some strains of green algae are able to synthesize secondary metabolites with anticancer properties (31). These bioproducts indicate the role of microalgae in drug discovery: a natural, renewable resource that can be used to answer some of the major global health challenges. Besides, microalgae are being widely used in animal feed for enhancing nutrition and boosting immunity among livestock, poultry, and aquaculture, thus providing an eco-friendly and nutrient-rich alternative to conventional feed sources.

6. Regional Studies on Microalgae in Coastal Andhra Pradesh (Chirala, Nellore, Machilipatnam)

Andhra Pradesh with a long coastline along the Bay of Bengal, presents a peculiar environmental condition for the growth of microalgae. Estuarine and mangrove ecosystems along with sandy beaches are highly present in the coastal areas of Chirala, Nellore, and Machilipatnam, which are considered ideal habitats for a wide diversity of species belonging to microalgae. This section considers the role of microalgae within these coastal ecosystems, taking into account the local environmental factors influencing algal growth, reviewing regional studies on the species of microalgae, and considering the wider environmental services contributed by these microorganisms. It also discusses how microalgae could be integrated into local environmental management strategies to underpin ecological health and sustainable development.

6.1. Environmental and Climatic Context of Andhra Pradesh

These ecosystems at Chirala, Nellore, and Machilipatnam experience variable environmental parameters-seasonal oscillations in temperature, salinity, nutrient condition, and differential monsoon rainfall-all having a direct consequence on microalgal abundance. The Andhra Pradesh coast experiences relatively high temperatures with considerable solar radiation, hence ideal for photosynthetic organisms like microalgae. Salinity levels in these waters may vary due to freshwater inputs from rivers and seasonal rainfall, which in turn affect the species composition and productivity (32). Further, nutrient inputs through riverine runoff, agriculture, and urbanization impinge on microalgal growth rates and community structure. These factors in combination make the coastal waters of Andhra Pradesh dynamic, productive in terms of microalgae, but at the same time challenging with regard to pollution and climate variability (33).

6.2. Local Studies on Microalgal Species and Ecosystem Functions

Various studies have documented microalgal diversity in the coastal waters of Andhra Pradesh, highlighting species that are most compatible with environmental conditions. For instance, at Chirala and Machilipatnam, high-density populations have been recorded with dominated diatoms, *cyanobacteria*, and green algae; these include species of *Chlorella, Nannochloropsis,* and *Spirulina* that have a prime importance in nutrient cycling and primary productivity. These microalgae provide a food base for zoo plankton and other marine animals. In Nellore, it is indicated that seasonal and human activities influence microalgal community composition, shifts in species composition due to fluctuation in nutrient load, and water quality. This fact is also highlighted in regional studies for the roles that these algae play in carbon sequestration and nutrient cycling, where they act like a natural bio filter, removing excessive nitrogen and phosphorus from coastal waters. Such findings draw the need for the protection of the habitat of these microalgae from climate change, pollution, and various coast developments in order not to interfere with its ecologic role.(34).

6.3. Micro algae in Coastal and Marine Ecosystem Services

Micro algae contribute significantly to the health of coastal and marine ecosystems in Andhra Pradesh by improving water quality, supporting biodiversity, and providing resilience against environmental stressors. Their capacity to absorb nutrients helps prevent eutrophication, maintaining water quality in regions affected by agricultural runoff and urban waste water. Furthermore, microalgae help support marine life by forming the base of the coastal food web, sustaining various species of fish, shellfish, and other marine organisms critical to local fisheries. These algae also assist in buffering ocean acidification by converting CO_2 into bicarbonates during photosynthesis, stabilizing pH levels, and protecting vulnerable marine organisms such as shellfish and coral. The potential for microalgae to contribute to climate change mitigation through carbon fixation and coastal habitat protection presents a valuable resource for addressing environmental challenges in these coastal regions. (35).

7. Challenges and Limitations in Utilizing Microalgae

While microalgae hold much promise for solving several environmental problems, a variety of technical, biological, and policy-related issues must be overcome if their full potential is to be exploited. Of all the challenges impeding scale-up of micro algal applications, the technical and Economic Barriers are the biggest. Large-scale microalgae cultivation requires huge investments in infrastructure, such as photo bioreactors or open ponds, and is extremely expensive due to the operation of controlled growth environments, nutrition, and continuous harvesting. Land and water requirements for large-scale cultivation can also be limiting factors, especially in regions where these resources are in short supply or very expensive. Another challenge is the efficient harvesting of microalgae, where methods for separating microalgal biomass from water have so far been energy-intensive and costly (36). Only with the solution of these economic problems will it be possible for the microalgae technologies to assume a position in broad applications.

Besides the economic constraints, the other most influential factors that affect microalgal systems are biological and environmental ones. Most of the microalgal species are sensitive to changes in the physical environment, such as temperature, salinity, light availability, and pollution levels, which influence growth and productivity. For instance, temperature fluctuations or increased pollution levels will stress microalgal communities and reduce their efficiency in carbon fixation or nutrient uptake (37). Besides, all microalgae strains are not equal for every purpose, and it remains one of the key challenges to screen for strains performing optimally in widely varied environmental conditions. There is a need for further research toward developing robust strains able to thrive under variable environmental conditions with no loss in efficiency.

8. Future Directions and Research Needs

Future development of microalgal applications is contingent on further progress in biotechnology, interactions among disciplines, and integration with other green technologies. Advances in genetic engineering and metabolic engineering might allow for the development of strains that are more resilient to environmental stresses while having a greater rate of carbon fixation or improved nutrient uptake capabilities (38). Efficiency and yield could also be further improved using selective breeding or synthetic biology for manifold applications of biofuels and bioproducts. Such will be necessary in the development of strong, high-performing microalgal strains for all kinds of environmental scenarios.

Compliance with ethical standards

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We the authors declare that there are no acknowledgements to disclose.

Disclosure of conflict of interest

All authors do not have any conflict of interest.

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