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A Green Solution: Microalgae for Soil health

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Abstract

Soil degradation in India, exacerbated by intensive agricultural practices and the Green Revolution, poses a significant threat to food security and environmental sustainability. This review highlights microalgae as a viable, eco-friendly solution for soil reclamation. Microalgae, particularly cyanobacteria, enhance soil fertility through nitrogen fixation, organic acid secretion, and biofilm formation, improving soil structure and nutrient availability. Additionally, phycoremediation—a process leveraging microalgae to remove contaminants—demonstrates potential in mitigating heavy metal pollution, salinization and erosion. This study synthesizes current research on microalgae-based remediation strategies and their practical applications, emphasizing their cost-effectiveness, adaptability and role in sustainable agriculture. By integrating microalgae into soil management practices, we can develop scalable, nature-based solutions to combat soil degradation, ensuring long-term agricultural productivity and environmental resilience.

Keywords: Soil health, Microalgae, Phycoremediation, Cyanobacteria, Sustainable agriculture.

Introduction

India, primarily an agricultural economy, relies heavily on healthy soil for sustainable food production. However, the Green Revolution, while increasing food production from 50 to 300 million tonnes, also led to significant soil degradation. This degradation is primarily due to erosion and waterlogging, which result in the loss of topsoil and salinization, respectively.

Soil reclamation is a crucial process that involves restoring degraded or contaminated soil to a healthy state capable of supporting plant growth. Maheswarappa*et al*. (2011) observed a decline in soil C-sustainability index following the Green Revolution, attributed to increased chemical input use. Additionally, excessive fertilizer application has led to nitrate accumulation and declining water tables. According to the National Bureau of Soil Survey and Land Use Planning, approximately 30% of India's land, or 146.8 million hectares, is degraded. This degradation results in substantial economic losses, estimated at around $3 billion annually due to salt-affected soils alone. With a significant population to feed and limited land resources, India faces a pressing need for effective soil reclamation strategies.

Soil reclamation aims to restore soil nutrients, fertility and structure to enhance agricultural productivity. Microalgae, particularly cyanobacteria and other algal species, have gained global attention for their potential in soil reclamation due to their ability to improve soil fertility, structure and contaminant removal. Various studies have demonstrated their effectiveness in restoring degraded lands across different regions.In China, a study has shown that cyanobacteria-based biocrusts play a crucial role in rehabilitating deserted lands by stabilizing soil, improving organic matter content and enhancing nitrogen fixation (Hu *et al*. 2021). Similarly, in Spain, microalgae-based biofertilizers, such as *Chlorella vulgaris*, have been found to improve soil microbial activity and increase crop productivity in degraded agricultural lands (González-Delgado andKhoshnevisan 2019). In arid regions of Africa, studies in Egypt and Algeria have demonstrated that algal biomass applications enhance soil organic matter, promote microbial diversity and boost crop yields under harsh environmental conditions (Essa *et al*. 2020). In developed nations such as the United States and European countries, research has explored integrating microalgae into organic farming practices. These studies highlight how algae-based amendments not only enrich the soil with essential nutrients but also reduce dependency on chemical fertilizers, making agricultural practices more sustainable (Gao *et al*. 2021). These global examples highlight the potential of microalgae in addressing soil degradation challenges across diverse environments. Given India's urgent need for sustainable soil reclamation solutions, leveraging microalgae-based technologies could provide an effective and eco-friendly approach to enhancing soil health, increasing agricultural productivity and ensuring long-term environmental resilience.

Causes of Soil Degradation

Soil degradation, a critical environmental issue, stems from both natural processes and human activities, profoundly impacting soil health and ecosystem stability. In India, as food grain production escalated over the decades, soil nutrient deficiencies have also risen alarmingly. While nitrogen (N) was the sole deficient element in Indian soils in 1950, by 2005–2006, the number of deficient nutrients had surged to nine, including nitrogen (N), phosphorus (P), potassium (K), sulphur (S), boron (B), copper (Cu), iron (Fe), manganese (Mn) and zinc (Zn) (Ministry of Agriculture 2006). This trend underscores the increasing strain on soil resources due to intensive agricultural practices and insufficient replenishment of essential nutrients (FAO 2015).

Natural processes, such as wind and water erosion, alongside human-induced activities like deforestation and improper land management, are leading causes of soil erosion. Erosion, particularly through water, remains the most significant degradation issue in India. It not only removes the nutrient-rich topsoil but also alters the terrain, making it less hospitable for plant growth (Pimentel and Burgess 2013). The combined impact of these factors has serious implications for agricultural productivity and ecological balance (Lal 2001).

Natural Causes of Soil Degradation

Natural phenomena are a substantial contributor to soil degradation. Events such as earthquakes, tsunamis, droughts, avalanches, landslides, volcanic eruptions, floods, tornadoes, and wildfires can cause significant soil displacement and loss of fertility. For instance, floods and landslides wash away topsoil, exposing subsoil layers that are often less fertile (FAO 2015). Similarly, droughts and wildfires can reduce organic matter and alter soil structure, leading to compaction and reduced permeability (Lal 2001). The frequency and intensity of such natural events, often exacerbated by climate change, highlight the vulnerability of soils to environmental changes (Pimentel and Burgess 2013).

Human-Induced Causes of Soil Degradation

Human activities are a major driver of soil degradation, with several factors contributing to the issue. Unsustainable land clearing and deforestation are significant contributors, stripping the soil of protective vegetation cover and exposing it to erosion (FAO 2015). Similarly, inappropriate agricultural practices such as excessive tillage, the use of heavy machinery and imbalanced application of inorganic fertilizers lead to structural damage and nutrient depletion (Lal 2001). Poor irrigation practices and pesticide overuse further exacerbate the problem by disrupting soil microbial communities and contributing to salinization (Pimentel and Burgess 2013). The inadequate incorporation of crop residues or organic matter into the soil and improper crop cycle planning also undermine soil fertility over time (Ministry of Agriculture 2006).

Industrial activities further aggravate soil degradation through contamination. Improper disposal of industrial waste, coupled with the use of hazardous chemicals and certain pesticides, can render soils unsuitable for agriculture or other beneficial uses. For example, heavy metals from industrial effluents accumulate in the soil, disrupting its natural composition and harming plant and microbial life (FAO 2015).

Salinization is another critical issue, often resulting from over-irrigation and poor water management. The excessive accumulation of salts in the soil alters its structure and impedes plant growth, posing a severe challenge in arid and semi-arid regions where irrigation is a necessity (Pimentel and Burgess 2013). Additionally, activities such as landfilling and mining can significantly disrupt soil structure and composition. Mining operations, in particular, often leave behind barren landscapes where vegetation struggles to thrive (Lal 2001). Urbanization further accelerates soil degradation through extensive land development and infrastructure projects. The construction of roads, buildings and other structures compacts soil and disrupts its natural processes. This urban sprawl not only reduces the area of arable land but also creates impermeable surfaces that increase runoff and erosion (FAO 2015).

Finally, abandoned or degraded agricultural lands reflect the long-term impacts of unsustainable farming practices. Continuous monoculture cropping, excessive reliance on chemical fertilizers and pesticide misuse degrade soil quality over time, reducing its ability to support productive agriculture. The lack of organic carbon inputs and failure to replenish essential nutrients further deplete soil health, making restoration efforts more challenging (Ministry of Agriculture 2006).

Thus, soil degradation is a multifaceted issue influenced by a complex interplay of natural and human-induced factors. Addressing this challenge requires integrated land management strategies, sustainable agricultural practices and stringent regulations on industrial and urban development to conserve soil health and ensure long-term ecological and agricultural sustainability. Efforts should focus on improving soil nutrient management, promoting afforestation, enhancing irrigation efficiency and mitigating the impacts of urbanization and industrialization. The need for such measures is particularly urgent in regions like India, where soil degradation poses a direct threat to food security and environmental health (FAO 2015; Pimentel and Burgess 2013).

Soil Reclamation Methods

Soil contamination is a critical environmental challenge that necessitates the implementation of robust remediation techniques to restore soil quality and prevent detrimental impacts on ecosystems and human health. Contaminants such as heavy metals, organic pollutants and toxic anions compromise soil productivity and pose long-term risks. Over the years, various remediation strategies have been developed to address this issue, each with distinct benefits and limitations. Selecting the most appropriate technique involves careful consideration of factors such as the type and concentration of contaminants, site-specific conditions, environmental implications and economic feasibility (Singh *et al.* 2013). Frequently, an integrated approach combining multiple methods is employed to achieve the desired outcomes effectively (Bhatnagar *et al.* 2011).

Physical Methods

Physical remediation strategies involve mechanical or structural interventions to contain or mitigate the impact of soil contamination. A prominent method is surface insulation, which entails covering the contaminated soil with a protective layer to prevent the spread of pollutants via wind or water erosion. Materials used for this barrier include synthetic fibers, clay, or concrete. By creating a physical shield, surface insulation limits contaminant mobility and reduces their interaction with surrounding environments. While effective for containment, this method does not eliminate contaminants and requires continuous monitoring and maintenance to ensure long-term efficacy (Qi *et al.* 2019).

Chemical Methods

Chemical remediation focuses on utilizing chemical agents to extract, stabilize, or neutralize contaminants within the soil matrix. One widely used technique is soil washing, also known as the hydraulic method. This method employs chemical solutions to each contaminant from the soil, effectively removing substances like heavy metals, radionuclides and organic pollutants. The choice of leaching agent depends on the nature of the pollutants, ranging from water for mild contamination to strong inorganic acids for persistent pollutants. Although soil washing can achieve high decontamination levels, it generates secondary waste, such as contaminated washing solutions, necessitating proper disposal or further treatment (FRTR 2020; Khan *et al*. 2018).

Biological Methods

Biological approaches leverage the natural capabilities of plants and microorganisms to degrade, immobilize, or remove contaminants, offering environmentally sustainable and cost-effective solutions for soil remediation.

Phytoremediation utilizes plants to stabilize or extract pollutants from the soil. In phytostabilization, plants immobilize contaminants within the soil by adsorbing them onto root surfaces and precipitating them in the rhizosphere. This approach prevents the migration of pollutants, particularly in erosion-prone areas. Another variant, phytoextraction, involves the uptake of contaminants by plant roots and their accumulation in aerial parts of the plant, which are subsequently harvested for safe disposal or treatment (Ali *et al*. 2013).

Bioremediation employs microorganisms to degrade organic and inorganic contaminants into less harmful substances. Techniques such as biofiltration utilize microbial communities housed in filters or bioreactors to break down pollutants in soil or water. Typical microorganisms include bacteria (e.g., *Streptomyces* spp. and pseudomonads), fungi (e.g., *Aspergillus* and *Penicillium*), and protozoa, which work synergistically to degrade a wide range of contaminants (Chowdhury *et al*. 2017). Similarly, air sparging, a subsurface remediation method, involves injecting pressurized air into contaminated groundwater to volatilize hydrocarbons, facilitating their extraction and removal (EPA, 2017).

Composting, another biological technique, involves mixing contaminated soil with organic matter to enhance microbial degradation of pollutants. Aerobic microorganisms break down organic contaminants, converting them into simpler compounds such as carbon dioxide and water. The composting process also enriches soil organic matter, improving its fertility and structure (Tremblay *et al*. 2019).

Phycoremediation represents an innovative approach to soil and water reclamation that leverages the abilities of algae to absorb and metabolize contaminants such as heavy metals, organic pollutants and nutrients. Algae like *Chlorella vulgaris*, *Nostoc* sp., and *Scenedesmus* are particularly effective due to their rapid growth, adaptability to diverse environments and ability to utilize solar energy for metabolic processes (Singh and Ahluwalia 2013). Key advantages of phycoremediation include environmental sustainability, as it aligns with natural biological processes and cost-effectiveness, as it requires minimal operational expenses compared to conventional methods (Bhatnagar *et al*. 2011). Additionally, phycoremediation avoids introducing harmful chemicals into the environment, making it a non-toxic alternative for soil reclamation (Bhola *et al*. 2014). The adaptability of algae allows them to thrive in a variety of contaminated sites and their use promotes biodiversity by creating new habitats for other organisms (Gupta *et al*. 2013). Moreover, phycoremediation reduces the risk of secondary pollution, a common issue in chemical-based treatments. It is an energy-efficient approach, as algae rely on photosynthesis, eliminating the need for external energy inputs. The versatility of this method enables its application to a wide array of pollutants, including heavy metals, nutrients and organic compounds, making it a promising solution for both urban and industrial contamination (Razzak *et al*. 2013; Mata *et al*. 2012). Several successful case studies worldwide have demonstrated the efficacy of phycoremediation in restoring contaminated soils and water bodies. In Tamil Nadu, researchers utilized *Chlorella vulgaris* to remediate heavy metal-contaminated soil near tannery industries, finding that the algae effectively reduced concentrations of chromium (Cr), lead (Pb) and cadmium (Cd) by over 70% within four weeks, highlighting its potential for industrial pollution management (Annamalai *et al*. 2018). Similarly, in Brazil, where mining activities have significantly contributed to soil contamination with toxic heavy metals such as mercury (Hg) and arsenic (As), a study on *Scenedesmus obliquus* demonstrated its ability to accumulate and detoxify these metals while simultaneously improving soil microbial diversity and fertility, emphasizing the potential of algal-based treatments in rehabilitating abandoned mining lands for agricultural use (Pereira *et al*. 2018). Meanwhile, in Australia, excessive irrigation has led to severe soil salinity issues, reducing farmland productivity. To address this challenge, researchers explored the application of *Dunaliella salina*, a salt-tolerant microalga, for salinity mitigation, revealing that it successfully absorbed excess salts, improved soil structure, and restored the fertility of previously unproductive lands, offering a promising solution for sustainable agriculture in salt-affected regions (Wang *et al.* 2019).

While physical and chemical methods provide effective containment and removal, biological approaches, particularly phycoremediation, offer sustainable, cost-effective and environmentally friendly solutions. Future research should focus on enhancing the efficiency of these methods, integrating innovative technologies, and addressing challenges related to scalability and long-term implementation. Collaborative efforts among scientists, policymakers, and local communities will be crucial in promoting sustainable soil management and restoring contaminated lands to their productive potential.

Strategies of Cyanobacteria in Soil Reclamation

Cyanobacteria, a group of photosynthetic prokaryotes, play an instrumental role in soil reclamation and phytoremediation through a range of ecological and biochemical mechanisms. Their ability to interact with and transform soil properties makes them indispensable in sustainable land management and rehabilitation practices. By enhancing soil fertility, improving structural stability and aiding in nutrient cycling, cyanobacteria offer a versatile and eco-friendly approach to addressing soil degradation and contamination issues (Singh 1961; Kaushik and Subhashini 1985).

Nitrogen Fixation for Enhanced Fertility

One of the key contributions of cyanobacteria to soil health is their ability to fix atmospheric nitrogen, a critical nutrient for plant growth. This unique capability, facilitated by specialized cells known as heterocysts, converts inert atmospheric nitrogen (N_2) into bioavailable forms like ammonium (NH_4^+), enriching nitrogen-deficient soils. This process not only supports plant growth but also reduces the dependency on synthetic nitrogen fertilizers, aligning with sustainable agricultural practices. For instance, species such as *Anabaena* and *Nostoc* are widely recognized for their nitrogen-fixing capabilities, particularly in marginal and degraded soils (Singh 1961; Kumar *et al.* 2020).

Soil Structure Enhancement

Cyanobacteria also contribute significantly to the physical improvement of soils. Their filamentous structures form networks that bind soil particles, enhancing aggregation and promoting better soil structure. This process improves soil porosity, increases water retention, and reduces susceptibility to erosion, particularly in sandy or loose soils. Such structural stabilization is vital in arid regions prone to desertification and erosion (Kaushik and Subhashini 1985; Pandhal*et al*. 2008). The role of cyanobacteria in binding soil particles also helps create microhabitats that support diverse microbial communities, further enhancing soil health.

Organic Acid Secretion and Mineral Weathering

Cyanobacteria play an essential role in mobilizing nutrients through the secretion of organic acids during metabolic processes. These organic acids facilitate the weathering of minerals, breaking them down into bioavailable forms that plants can readily absorb. This mechanism not only enhances nutrient accessibility but also contributes to the development of soil profiles in degraded lands. For example, the release of compounds like citric and oxalic acids by certain cyanobacterial species aids in dissolving phosphates and other essential minerals, thereby enriching the soil nutrient pool (Singh 1961; Mishra and Rai 2015).

Biofilm Formation and Soil Stabilization

Another critical strategy employed by cyanobacteria is biofilm formation. These biofilms, formed on the soil surface, create a protective layer that shields the underlying soil from erosion caused by wind and water. Biofilms also reduce the loss of organic matter and nutrients, which is particularly beneficial in degraded or nutrient-poor soils. This stabilization effect is vital in arid environments where soil erosion is a significant concern. Cyanobacteria such as *Scytonema* and *Nostoc* have been observed to form resilient biofilms that effectively prevent soil degradation (Pandhal*et al*. 2008; Yadav *et al*. 2022).

Alkaline Substance Production and pH Regulation

In acidic soils, where high hydrogen ion concentration limits plant growth, cyanobacteria contribute by producing alkaline substances. These substances help neutralize soil acidity, creating a more hospitable environment for plant roots and associated microorganisms. This pH regulation capability is particularly valuable in rehabilitating acidic soils in agricultural and mining-affected areas (Singh 1961; Priyadarshanee *et al*. 2020).

Microbial Interactions and Soil Biodiversity

Cyanobacteria establish symbiotic and mutualistic relationships with other microorganisms, enhancing microbial diversity and soil fertility. These interactions foster a balanced ecosystem where various microbial species contribute to nutrient cycling, decomposition and organic matter accumulation. For instance, cyanobacteria often associate with nitrogen-fixing bacteria and mycorrhizal fungi, amplifying their collective benefits for soil and plant health (Singh, 1961; Gupta *et al*. 2013).

Carbon Sequestration and Climate Mitigation

Through photosynthesis, cyanobacteria absorb atmospheric carbon dioxide (CO_2) and convert it into organic carbon compounds, contributing to soil organic matter and carbon sequestration. This process not only mitigates climate change by reducing greenhouse gas levels but also enhances soil carbon content, which is vital for maintaining soil fertility and water retention (Singh, 1961; Mishra and Rai, 2015). Cyanobacterial contributions to carbon dynamics underscore their role in promoting sustainable land-use practices.

Multifunctional Roles and Biofertilizer Potential

Cyanobacteria also produce bioactive compounds, including plant hormones like auxins and gibberellins, which stimulate plant growth and suppress pests and pathogens. Their biomass can be harvested and processed into biofertilizers, providing a sustainable alternative to synthetic fertilizers. Cyanobacteria-derived biofertilizers have shown potential to enhance soil microbial activity, improve nutrient availability, and promote plant development, thereby reducing reliance on chemical inputs (Kaushik and Subhashini1985; Bhola *et al*. 2014).

Recent research highlights the potential of cyanobacterial biocrusts in improving soil fertility and plant productivity. For example, Yadav *et al*. (2022) conducted experiments using *Nostoccalcicolea* and *Scytonema*sp. inoculated into different soil types, including coarse sand, fine sand, and loamy soil. Their findings revealed that cyanobacterial consortia significantly enhanced fertility in sandy soils and promoted superior plant growth in loamy soils compared to individual strains. This study underscores the viability of using cyanobacterial biocrusts as a cost-effective and eco-friendly strategy for land rehabilitation and soil health improvement.Cyanobacteria offer a suite of ecological and biochemical strategies for soil reclamation, ranging from nitrogen fixation and structural stabilization to nutrient cycling and carbon sequestration. Their multifunctional roles make them invaluable in addressing soil degradation and contamination while supporting sustainable agricultural practices. Future research should focus on optimizing cyanobacterial applications for large-scale soil restoration projects and integrating their use into holistic land management strategies.

Conclusion and prospects

Technological advancements hold transformative potential for modern agriculture, offering innovative solutions to critical challenges such as soil degradation and declining soil fertility. Among these advancements, phycoremediation stands out as an environmentally friendly and sustainable approach to restoring soil health. This technique harnesses the natural abilities of microalgae and cyanobacteria to detoxify and rejuvenate contaminated or degraded soils, providing an effective alternative to chemical-intensive methods. The successful application of phycoremediation in various regions globally highlights its potential in addressing soil contamination, improving soil fertility and promoting sustainable agricultural practices. From heavy metal remediation in industrially polluted soils to restoring nutrient balance in degraded farmlands, microalgae have demonstrated their adaptability and efficiency in soil reclamation. However, large-scale implementation requires further research on optimizing algal strains, improving cultivation techniques and integrating this method into existing agricultural frameworks. To maximize the benefits of phycoremediation, a concerted effort is required from all stakeholders. Policymakers must prioritize research funding, create supportive policies, and facilitate large-scale implementation through incentives and subsidies for sustainable agricultural practices. Farmers should be encouraged to adopt microalgae-based remediation techniques by providing them with accessible training programs and financial assistance. Meanwhile, researchers must continue exploring innovative ways to enhance the efficiency of microalgae in diverse environmental conditions, ensuring their practical application in real-world scenarios. By integrating eco-friendly approaches like phycoremediation into mainstream agricultural practices, we can mitigate soil degradation, enhance long-term soil productivity, and ensure food security. This holistic approach not only supports environmental conservation but also empowers farming communities by reducing dependence on chemical fertilizers and enhancing soil resilience against climate change. Collaboration among governments, agricultural institutions and local communities will be key to making microalgae-based soil remediation a widespread and impactful reality. The future of agriculture lies in sustainable innovations and phycoremediation represents a promising step toward achieving a balance between productivity and environmental stewardship.

"In this handful of soil is your future. Take care of it; it will take care of you. Destroy it, and it will destroy you" (a quote from Veda).

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