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Harnessing Edaphic Microalgae for Soil Carbon Sequestration and Climate-smart Agriculture

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Author's contribution

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Edaphic microalgae are emerging as critical components in climate-smart agriculture due to their multifaceted roles in enhancing soil health, sequestering carbon, and improving agricultural sustainability. These microorganisms, including cyanobacteria, green algae, and diatoms, fix atmospheric carbon through photosynthesis and contribute to the formation of soil organic matter (SOM) by releasing biomass and extracellular polymeric substances (EPS). Their ability to enhance soil aggregation, improve nutrient cycling, and stabilize carbon makes them essential in mitigating climate change. Advances in microalgal cultivation techniques, such as photobioreactors and biofilm-based systems, have improved their scalability, while omics technologies provide insights into their genetic and metabolic pathways, enabling bioengineering for enhanced functionality. Field studies demonstrate significant benefits, including increases in soil organic carbon by 15–30% and crop yield improvements of up to 20% when microalgae are applied as biofertilizers. Challenges such as environmental limitations, competition with other soil microorganisms, and high production costs hinder their widespread adoption. Future lie in exploring diverse microalgal species, developing cost-effective cultivation systems, and integrating microalgae into multifunctional agricultural systems like agroforestry and aquaponics. Policy support, including financial incentives and standardized regulations, will be instrumental in fostering adoption. Remote sensing and modelling tools further enhance the feasibility of large-scale applications, enabling precise monitoring of microalgal activity and contributions to soil carbon dynamics. Despite current limitations, the potential of edaphic microalgae to revolutionize sustainable agriculture is immense, offering scalable solutions to global challenges such as soil degradation, climate change, and food insecurity. With continued research, innovation, and interdisciplinary collaboration, edaphic microalgae could serve as a cornerstone for achieving resilience and sustainability in agriculture, aligning with global climate action goals and fostering long-term environmental and economic benefits.

Keywords: Edaphic microalgae; carbon sequestration; biofertilizers; soil health.

1. INTRODUCTION

A. Climate-smart Agriculture and its Significance

Climate-smart agriculture (CSA) has emerged as a transformative approach to mitigate the adverse impacts of climate change on agricultural systems while ensuring food security and promoting sustainability (Hellin et al., 2023). Climate-smart agriculture encompasses a range of techniques and approaches that promote sustainable and climate-resilient farming practices (Kenduiwa et al., 2024; Hoque et al., 2023). Defined by the Food and Agriculture Organization (FAO), CSA is an integrative methodology aimed at increasing agricultural productivity, enhancing resilience, and reducing greenhouse gas emissions where possible. With a projected global population of over 9 billion by 2050, the agricultural sector faces a daunting challenge to meet food demands while minimizing environmental footprints. Current agricultural practices contribute significantly to global greenhouse gas emissions, accounting for approximately 17–20% of total emissions. CSA addresses this challenge by integrating advanced technologies, improved crop management practices, and sustainable land-use strategies (Hussain et al., 2022). The incorporation of biological processes such as carbon sequestration, nutrient cycling, and ecosystem services into CSA frameworks ensures a balance between productivity and environmental stewardship. Key components of CSA include conservation agriculture, agroforestry, precision farming, and innovations such as biofertilizers and soil amendments, positioning it as a cornerstone for achieving climate resilience in agriculture.

B. Importance of Soil Carbon Dynamics in Mitigating Climate Change

Soil carbon dynamics play a pivotal role in the global carbon cycle and climate regulation, acting

Table 1. Importance of Soil Carbon Dynamics in Mitigating Climate Change (Source- Lal et al., 2021)

Aspect	Description	Mechanism Involved	Impact on Climate Change Mitigation
Soil as a Carbon Sink	Soils store large amounts of organic and inorganic carbon.	Carbon sequestration through microbial activity and plant inputs.	Reduces atmospheric CO_2 levels, slowing global warming.
Soil Organic Carbon (SOC) Stabilization	Long-term storage of carbon in stable soil fractions.	Formation of humus, mineral associations, and microbial decomposition.	Enhances soil fertility and prevents rapid CO_2 release.
Role of Microbial Communities	Microbes mediate decomposition and carbon transformation.	Enzyme-driven carbon cycling, nutrient mineralization.	Influences carbon stability and greenhouse gas emissions.
Carbon Loss via Soil Respiration	Microbial breakdown of organic matter releases CO_2.	Heterotrophic respiration, temperature sensitivity.	Regulates CO_2 flux, affecting atmospheric carbon balance.
Influence of Land Use and Management	Agricultural practices and deforestation impact soil carbon stocks.	Tillage, organic amendments, cover cropping.	Determines carbon sequestration potential and soil degradation rates.
Interaction with Climate Factors	Temperature, moisture, and vegetation affect carbon turnover.	Warming-induced decomposition, drought effects.	Alters sequestration efficiency and feedback to climate change.
Carbon Sequestration Strategies	Methods to enhance soil carbon storage.	Biochar application, conservation tillage, reforestation.	Improves soil health and mitigates climate change effects.

as both a source and a sink for atmospheric carbon dioxide (CO_2) (Table 1) (Lal et al., 2021). Globally, soils store approximately 2,500 gigatons (Gt) of carbon, which is nearly three times the amount found in the atmosphere and four times that in biomass. The dynamic balance between carbon inputs through organic matter deposition and outputs via respiration and decomposition determines soil carbon sequestration potential. Enhancing soil carbon sequestration can offset a significant portion of anthropogenic CO_2 emissions, with an estimated sequestration potential of 1.5–3 Gt CO_2 per year through improved land management practices. The decomposition of organic matter and subsequent stabilization in soil aggregates ensure the long-term storage of carbon, which not only mitigates climate change but also improves soil fertility, water retention, and microbial activity. Strategies such as no-till farming, cover cropping, and the application of organic amendments have shown to increase soil organic carbon (SOC) levels, further emphasizing the critical role of soil carbon dynamics in sustainable agriculture (Schmidt et al., 2018).

C. Introduction to Edaphic Microalgae and Their Ecological Role in Soils

Edaphic microalgae, encompassing diverse groups such as cyanobacteria, chlorophytes, and diatoms, are microscopic, photosynthetic organisms inhabiting the soil matrix. These organisms are integral to soil ecosystems, contributing to primary productivity, nutrient cycling, and soil stabilization. Cyanobacteria, are known for their nitrogen-fixing capabilities, making them crucial for maintaining soil fertility in nutrient-poor environments (Nawaz et al., 2024). Through photosynthesis, edaphic microalgae fix atmospheric CO_2, contributing to the soil organic carbon pool and facilitating carbon sequestration. Furthermore, their extracellular polymeric substances (EPS) enhance soil aggregation and water retention, thus improving soil structure and resilience to erosion. The ability of microalgae to adapt to varying environmental conditions, including arid and nutrient-deficient soils, underscores their ecological significance. Studies have demonstrated that soils with higher microalgal biomass exhibit improved nutrient availability and reduced greenhouse gas emissions, highlighting their potential as a tool for sustainable soil management (Suleiman et al., 2020).

D. Objectives and Scope of the Review

This review aims to provide an in-depth analysis of the role of edaphic microalgae in soil carbon dynamics and their potential applications in climate-smart agriculture. The specific objectives include: Exploring the diversity and ecological functions of edaphic microalgae in soil ecosystems. Examining the mechanisms through which these microorganisms influence soil carbon sequestration. Evaluating the integration of microalgae-based technologies into CSA practices for enhanced sustainability and resilience (Toor et al., 2024). Identifying research gaps and future directions to harness the full potential of edaphic microalgae in addressing global climate challenges.

2. EDAPHIC MICROALGAE

A. Definition and Classification of Edaphic Microalgae

Edaphic microalgae are microscopic, photosynthetic organisms residing within soil ecosystems, contributing significantly to soil ecology and biogeochemical processes. These organisms include a diverse range of taxa such as cyanobacteria, green algae (Chlorophyta), and diatoms, which play crucial roles in nutrient cycling, carbon fixation, and soil stabilization. Unlike aquatic microalgae, edaphic microalgae are adapted to terrestrial environments, where they thrive within soil interstices, biofilms, and crusts (Kamal et al., 2010). Classification of edaphic microalgae is primarily based on their pigmentation, cell structure, and physiological characteristics. Cyanobacteria are prokaryotic and often nitrogen-fixing, while Chlorophyta and diatoms are eukaryotic, differing in their chloroplast structures and photosynthetic pathways. These organisms are classified into several phyla, with notable genera such as *Nostoc* and *Anabaena* in cyanobacteria, *Chlorella* in Chlorophyta, and *Navicula* in diatoms. Their unique physiological and morphological traits enable them to adapt and contribute to soil fertility and structure under varying environmental conditions (Lambers et al., 2006).

B. Types of Microalgae Found in Soil Ecosystems

i. Cyanobacteria

Cyanobacteria are among the most primitive photosynthetic organisms, with a lineage dating back over 2.5 billion years. They are capable of fixing atmospheric nitrogen through specialized cells called heterocysts, which play a pivotal role in maintaining soil fertility, especially in arid and semi-arid regions. Cyanobacteria such as *Nostoc*, *Anabaena*, and *Microcoleus* are prominent in soil environments, particularly in biocrusts, where they form dense networks contributing to soil stabilization and moisture retention (Rossi et al., 2022). They produce extracellular polymeric substances (EPS) that enhance soil aggregation, thereby reducing erosion and increasing carbon sequestration potential. Cyanobacteria also exhibit tolerance to extreme environmental conditions such as high UV radiation and desiccation, making them indispensable in soil rehabilitation programs.

ii. Chlorophyta

Chlorophyta, or green algae, are eukaryotic microalgae that thrive in various soil environments due to their efficient photosynthetic machinery. Genera such as *Chlorella*, *Scenedesmus*, and *Trebouxia* are commonly found in soil ecosystems, where they contribute to primary production and carbon fixation. Chlorophyta are known for their rapid growth rates and adaptability to fluctuating environmental conditions, including pH, temperature, and moisture levels (Aigner et al., 2020). Unlike cyanobacteria, Chlorophyta lack nitrogen-fixing capabilities but significantly contribute to organic matter build up by assimilating CO_2 into complex carbohydrates and lipids. Their role in nutrient cycling and symbiotic associations with fungi to form lichens further underscores their ecological importance.

iii. Diatoms

Diatoms are unicellular, eukaryotic algae characterized by their silica-based cell walls, known as frustules, which exhibit intricate patterns. Common genera such as *Navicula*, *Pinnularia*, and *Achnanthes* inhabit soils, particularly in moist and nutrient-rich environments. Diatoms are significant contributors to soil carbon dynamics due to their high photosynthetic efficiency and ability to sequester CO_2 into organic carbon forms (Hori et al., 2019). Their frustules not only enhance soil structure but also provide microhabitats for other microorganisms. Diatoms are sensitive indicators of soil health, responding to changes in moisture, pH, and nutrient availability, making them valuable for ecological monitoring and restoration efforts.

C. Habitat Preferences and Adaptations to Terrestrial Ecosystems

Edaphic microalgae exhibit remarkable adaptability to terrestrial ecosystems, thriving across diverse habitats ranging from arid deserts to fertile agricultural fields. They colonize soil surfaces, forming biofilms and biocrusts that protect against erosion and desiccation. Adaptations such as the production of EPS, spore formation, and specialized pigments enable them to withstand extreme conditions such as high UV radiation, temperature fluctuations, and nutrient scarcity (Priscilla et al., 2024). Cyanobacteria, produce UV-absorbing compounds such as scytonemin, while Chlorophyta can enter dormant stages under unfavourable conditions. Soil pH, moisture content, and organic matter are critical determinants of their distribution and activity. In arid regions, microalgae contribute to water retention and nutrient cycling, while in agricultural soils, they enhance fertility and organic carbon pools.

D. Role in Primary Production and Ecosystem Stability

Edaphic microalgae are primary producers in soil ecosystems, converting solar energy and CO_2 into organic matter through photosynthesis. They form the base of the soil food web, supporting heterotrophic organisms and enhancing nutrient availability. Their contributions to soil carbon pools are significant, with cyanobacteria alone fixing an estimated 25–30 kg of carbon per hectare annually in arid soils (Thomas et al., 2008). By stabilizing soil particles through EPS production and forming soil aggregates, they prevent erosion and maintain soil structure. Their interactions with other soil microorganisms, such as bacteria and fungi, foster nutrient cycling and improve overall soil health. The ecological functions of edaphic microalgae are integral to sustaining soil fertility, resilience, and ecosystem services, making them key players in maintaining the stability and productivity of terrestrial ecosystems.

3. SOIL CARBON DYNAMICS: MECHANISMS AND PROCESSES

A. Definition and Components of Soil Carbon Pools

Soil carbon dynamics refer to the movement, storage, and transformation of carbon within soil ecosystems, playing a pivotal role in global carbon cycling. The soil carbon pool, which stores approximately 2,500 gigatons (Gt) of carbon, surpasses the carbon content in vegetation (650 Gt) and the atmosphere (750 Gt) combined. Soil carbon is classified into three primary pools based on its turnover rate and stability: active, slow, and passive. Each pool contributes differently to soil health, fertility, and carbon sequestration potential (Gulde et al., 2008).

i. Active carbon

The active carbon pool represents the most labile fraction of soil carbon, comprising organic compounds with turnover times of days to months. It includes microbial biomass, root exudates, and decomposing plant residues, which serve as a readily available energy source for soil microbes (Khatoon et al., 2017). Active carbon contributes significantly to nutrient cycling, particularly nitrogen and phosphorus availability, and is a key indicator of soil health due to its rapid response to environmental changes. Despite its small proportion in total soil carbon (~1–5%), the active pool plays a crucial role in ecosystem functions and short-term carbon dynamics.

ii. Slow carbon

The slow carbon pool consists of partially decomposed organic matter with intermediate turnover rates ranging from years to decades (Robertson et al., 2000). This pool includes humic substances such as fulvic and humic acids, which are relatively stable but still subject to microbial degradation. Slow carbon is vital for maintaining soil structure, water-holding capacity, and nutrient retention. It serves as a transitional pool, linking active and passive carbon pools and ensuring the continuous supply of nutrients to plants and microbes.

iii. Passive carbon

The passive carbon pool is the most stable and recalcitrant fraction of soil carbon, with turnover times of hundreds to thousands of years (Dynarski et al., 2020). This pool is primarily composed of chemically complex compounds such as charcoal, lignin derivatives, and mineral-associated organic matter (MAOM). Passive carbon contributes to long-term carbon storage, making it crucial for mitigating climate change. It represents approximately 60–80% of total soil organic carbon (SOC) in many soils and is tightly bound to soil minerals, protecting it from microbial decomposition.

B. Biogeochemical Cycles Involved in Soil Carbon Dynamics

i. Carbon sequestration processes

Carbon sequestration in soils involves the transfer of atmospheric CO_2 into the soil carbon pool, primarily through photosynthesis and subsequent incorporation into plant residues and microbial biomass. Carbon inputs include root exudates, leaf litter, and organic amendments, which are transformed into SOC through microbial activity. No-till farming, cover cropping, and agroforestry practices enhance carbon sequestration by increasing organic matter inputs and reducing carbon losses (Nair et al., 2010). Globally, soils have the potential to sequester 1.5–3 Gt CO_2annually through improved land management practices, offsetting a significant portion of anthropogenic emissions.

ii. Organic matter decomposition

Decomposition is a key process in soil carbon dynamics, involving the breakdown of organic matter by soil microorganisms into simpler compounds such as CO_2, water, and nutrients. The decomposition rate depends on factors such as soil temperature, moisture, and organic matter quality. Labile carbon compounds decompose rapidly, while recalcitrant compounds require specialized microbial enzymes and longer turnover times. During decomposition, a portion of organic carbon is stabilized in soil aggregates or mineral-associated fractions, contributing to long-term carbon storage (Jastrow et al., 2018).

C. Role of Soil Microbes in Carbon Turnover

Soil microbes, including bacteria, fungi, and archaea, are central to carbon turnover, driving the decomposition of organic matter and the stabilization of SOC. Microbial respiration accounts for approximately 50–70% of soil CO_2 emissions, making it a critical component of soil-atmosphere carbon exchange. Fungi, particularly mycorrhizal fungi, play a unique role in carbon storage by forming hyphal networks that contribute to soil aggregation and the sequestration of recalcitrant carbon. Bacteria, on

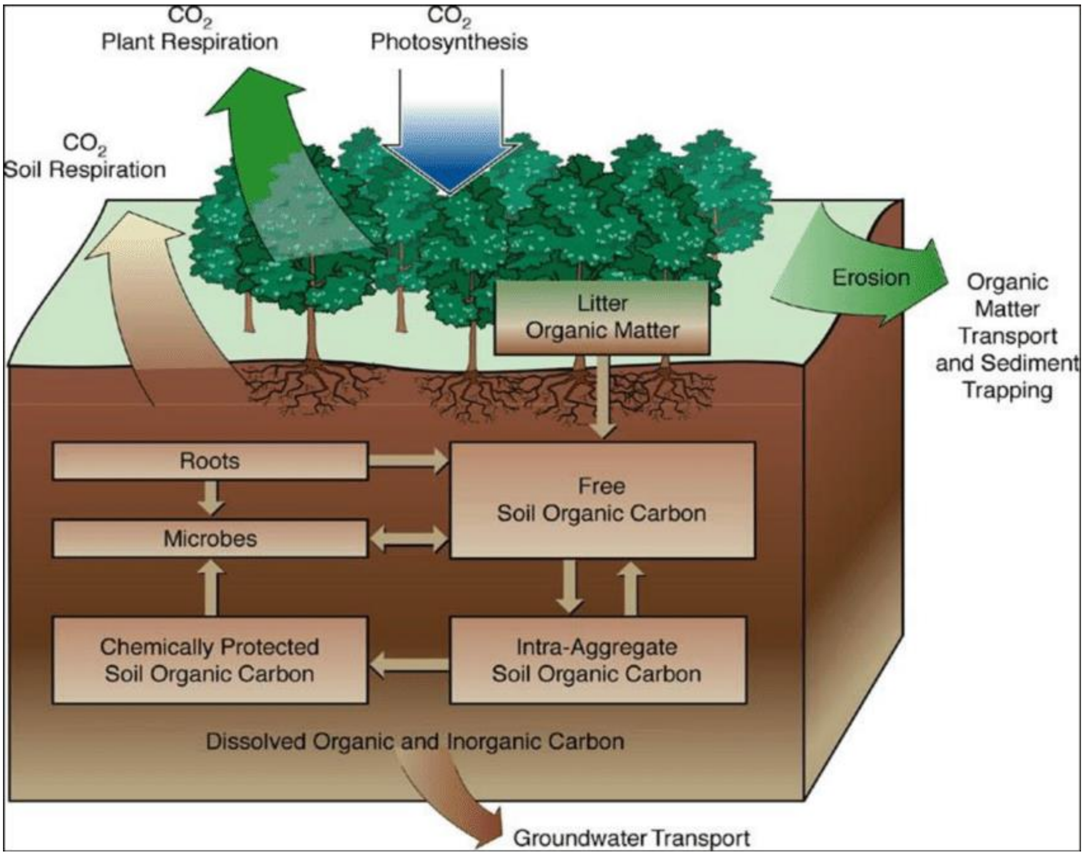

Fig. 1. Soil Carbon Sequestration (Source- IJCS)

the other hand, are more involved in the rapid turnover of labile carbon (Li et al., 2023). The microbial efficiency-matrix stabilization (MEMS) framework highlights the importance of microbial activity in stabilizing carbon through interactions with soil minerals and the production of resistant microbial-derived organic matter.

D. Interactions between Soil Physical, Chemical, and Biological Processes

Soil carbon dynamics are governed by complex interactions among physical, chemical, and biological processes (Srivastava et al., 2018). Soil texture, structure, and mineralogy influence carbon stabilization by determining the accessibility of organic matter to microbes and enzymes. Fine-textured soils with high clay content are more effective in protecting organic carbon through mineral association and aggregate formation. Chemical properties such as pH and cation exchange capacity affect nutrient availability and microbial activity, indirectly influencing carbon turnover. Biological processes, including root exudation and microbial interactions, drive the decomposition and transformation of organic matter. For example, the rhizosphere, enriched with root-derived carbon, supports a diverse microbial community that enhances nutrient cycling and carbon sequestration (Fan et al., 2022).

4. ROLE OF EDAPHIC MICROALGAE IN SOIL CARBON SEQUESTRATION

A. Carbon Fixation Through Photosynthesis

Edaphic microalgae play a crucial role in soil carbon sequestration through their photosynthetic capabilities, converting atmospheric carbon dioxide (CO_2) into organic carbon (Table 2). These microorganisms, including cyanobacteria, green algae, and diatoms, utilize light energy to fix carbon into carbohydrates and other organic compounds. The photosynthetic efficiency of microalgae is notably high, with cyanobacteria, capable of fixing up to 10–20 grams of carbon per square meter annually in arid soils. This contribution is particularly significant in soil crusts and degraded ecosystems where plant cover is minimal.

Table 2. Role of Edaphic Microalgae in Soil Carbon Sequestration (Source: Alvarez et al., 2021, Popa et al., 2022)

Aspect	Description	Mechanism Involved	Impact on Soil Carbon Sequestration
Definition of Edaphic Microalgae	Microalgae inhabiting soil, including cyanobacteria, chlorophytes, and diatoms.	Adaptation to terrestrial environments, biofilm formation.	Provides primary productivity and initiates carbon cycling in soils.
Carbon Fixation Mechanisms	Conversion of atmospheric CO_2 into organic carbon via photosynthesis.	Light-dependent reactions, Calvin cycle.	Enhances soil carbon pools and contributes to long-term sequestration.
Soil Organic Carbon (SOC) Accumulation	Deposition of stable organic matter through biomass turnover and exudation.	Secretion of extracellular polymeric substances (EPS), microbial interactions.	Increases SOC storage, reduces carbon loss.
Microalgal-Microbial Interactions	Symbiotic and mutualistic relationships with soil microbes.	Nutrient exchange, biofilm development.	Enhances carbon stabilization and microbial carbon use efficiency.
Contribution to Soil Structure	Improvement of soil aggregation and erosion resistance.	EPS production, particle binding.	Reduces soil degradation, promoting long-term carbon storage.
Influence on Soil Respiration	Regulation of CO_2 emissions through algal and microbial respiration.	Carbon cycling, microbial mineralization.	Balances carbon input and output, minimizing CO_2 loss.
Environmental Factors Affecting Sequestration	Influence of light, moisture, temperature, and nutrient availability.	Adaptation to extreme conditions, dormancy strategies.	Affects efficiency and stability of carbon sequestration processes.

Cyanobacteria such as *Microcoleusvaginatus* and *Nostoc* dominate biological soil crusts, forming the primary photosynthetic organisms in these environments. In agricultural systems, the incorporation of microalgae as biofertilizers or soil amendments has been shown to enhance carbon inputs, directly contributing to the soil organic carbon (SOC) pool (Alvarez et al., 2021).

B. Contribution to Soil Organic Matter Formation

Microalgae contribute to the formation of soil organic matter (SOM) through the deposition of biomass and extracellular polymeric substances (EPS) (Ramakrishnan et al., 2023). Upon senescence, algal cells release organic carbon, including polysaccharides, proteins, and lipids, which integrate into the soil matrix as particulate organic matter. This process enhances the labile carbon fraction, promoting microbial activity and nutrient cycling. The EPS produced by microalgae, comprising complex carbohydrates and glycoproteins, serves as a precursor to stable SOM. In desert soils, cyanobacteria have been observed to increase SOM content by 2–5% over several years, significantly improving soil fertility. The presence of microalgal biomass stimulates the activity of heterotrophic microbes, accelerating the decomposition and transformation of organic material into humic substances, which are critical for long-term carbon storage (Popa et al., 2022).

C. Influence on Soil Aggregation and Stabilization of Carbon

The role of edaphic microalgae in soil aggregation is primarily mediated through the production of EPS, which binds soil particles together to form aggregates. These aggregates protect SOC from microbial decomposition by physically occluding organic matter within their structure. Studies have shown that soils dominated by cyanobacteria exhibit increased aggregate stability, reducing erosion and enhancing water retention. Aggregate formation also facilitates the stabilization of carbon in mineral-associated forms, a key mechanism for long-term carbon sequestration. In arid and semi-arid regions, microalgal biofilms have been reported to decrease soil erosion by up to 60%, indirectly preventing carbon loss through surface runoff. The stabilization of SOC within aggregates and mineral fractions is critical for maintaining soil health and mitigating CO_2 emissions, particularly in vulnerable ecosystems.

D. Synergistic Interactions with Other Soil Microorganisms

Edaphic microalgae interact synergistically with other soil microorganisms, including bacteria, fungi, and archaea, enhancing carbon sequestration processes (Abinandan et al., 2019). These interactions facilitate the transfer of carbon and nutrients within the soil food web, promoting microbial diversity and activity. Cyanobacteria, form mutualistic relationships with heterotrophic bacteria that decompose organic matter, releasing nutrients that are then utilized by the algae. The association between microalgae and mycorrhizal fungi enhances soil structure and nutrient cycling, further contributing to SOC stabilization. In biological soil crusts, these synergistic relationships create a microhabitat that supports the co-existence and productivity of diverse microbial communities, amplifying carbon sequestration rates. Microalgal biofilms provide a continuous source of organic carbon, sustaining microbial communities and driving the formation of recalcitrant carbon compounds (Mandal et al., 2021).

5. POTENTIAL APPLICATIONS IN CLIMATE-SMART AGRICULTURE

A. Enhancing Soil Fertility and Productivity Through Microalgae-Based Biofertilizers

Microalgae-based biofertilizers are emerging as a sustainable alternative to chemical fertilizers, addressing the twin challenges of declining soil fertility and environmental degradation. Edaphic microalgae such as cyanobacteria (*Anabaena*, *Nostoc*, *Microcoleus*) and green algae (*Chlorella*, *Scenedesmus*) are widely recognized for their ability to fix atmospheric nitrogen, solubilize phosphate, and enhance nutrient availability. Cyanobacteria, can fix up to 60 kg of nitrogen per hectare annually, significantly reducing dependency on synthetic fertilizers. Microalgae excrete bioactive compounds, including phytohormones such as auxins and gibberellins, which promote root growth and improve plant nutrient uptake. Field studies have demonstrated the efficacy of microalgae-based biofertilizers in enhancing crop yields. For example, rice fields inoculated with cyanobacteria showed a 10–15% increase in grain yield compared to non-inoculated fields. The application of *Chlorella vulgaris* as a biofertilizer has also been reported to improve soil organic matter by 20% and enhance soil microbial activity. These biofertilizers not only replenish soil nutrients but also improve soil structure and water retention, making them an integral component of climate-smart agriculture (Bhattacharyya et al., 2020).

B. Carbon Sequestration and Climate Change Mitigation Strategies

Edaphic microalgae are key players in carbon sequestration strategies, contributing to the reduction of atmospheric CO_2 levels. Through photosynthesis, microalgae assimilate CO_2 into organic compounds, which are subsequently incorporated into the soil carbon pool. Cyanobacteria, can fix carbon at rates of 0.6–2.4 g m^{-2} day^{-1} in biological soil crusts, making them effective agents for carbon capture in degraded landscapes. The deployment of microalgae-based soil amendments in agricultural systems can enhance carbon sequestration (Alvarez et al., 2021). Biochar enriched with microalgal biomass has been shown to increase soil organic carbon by up to 30% while simultaneously reducing greenhouse gas emissions. Moreover, microalgae-based technologies have been integrated into greenhouse gas mitigation frameworks, with studies demonstrating a 50% reduction in soil nitrous oxide emissions due to the presence of cyanobacterial biofilms. These strategies align with the goals of climate-smart agriculture by simultaneously enhancing productivity and mitigating climate change impacts.

C. Integration into Sustainable Farming Practices

The incorporation of microalgae into sustainable farming practices offers multiple benefits, ranging from soil health improvement to resource conservation (Renuka et al., 2018). In organic farming, microalgae are used as bio stimulants to enhance crop resilience against abiotic stressors such as drought and salinity. The use of algal inoculants in conservation agriculture has been shown to increase soil aggregate stability by 40–60%, reducing erosion and enhancing water infiltration. Microalgae also play a role in integrated nutrient management systems, complementing organic and inorganic fertilizers to optimize nutrient use efficiency. For example, the co-application of microalgae with compost has been reported to improve nitrogen use efficiency by 25% and reduce nutrient leaching losses (La Bella et al., 2024). In precision agriculture, microalgae-based bioproducts are used to create site-specific solutions for nutrient deficiencies, enhancing sustainability and reducing environmental footprints.

D. Potential for Biotechnological Exploitation in Carbon-rich Soil Amendments

The biotechnological potential of microalgae in developing carbon-rich soil amendments is vast, offering innovative solutions for sustainable agriculture. Algal biomass can be processed into biochars, composts, and soil conditioners, which improve soil carbon stocks and fertility. Microalgae-derived biochar, characterized by its high carbon content and porosity, enhances soil water retention and provides a stable carbon reservoir. Algal biomass is rich in polysaccharides, proteins, and lipids, making it an excellent substrate for producing organic amendments that enhance soil microbial activity and nutrient cycling (Song et al., 2022). The use of microalgae in wastewater treatment systems provides a dual benefit by recycling nutrients into algal biomass and producing a nutrient-rich soil amendment. Wastewater-grown *Scenedesmus* and *Chlorella* have been successfully used to create composts with a 25–30% higher nitrogen content than traditional composts. Advanced biotechnological approaches, such as genetic engineering, are being explored to enhance the carbon fixation and nutrient cycling capabilities of microalgae, paving the way for more efficient and cost-effective applications in agriculture.

6. CHALLENGES AND LIMITATIONS

A. Environmental Factors Influencing Microalgal Activity

i. Soil moisture and temperature

Soil moisture and temperature are critical determinants of microalgal activity and distribution. Edaphic microalgae, such as cyanobacteria and green algae, are highly sensitive to desiccation and thermal extremes, which limit their growth and carbon sequestration potential. Studies have shown that microalgal photosynthesis and nitrogen fixation rates decrease significantly under low moisture conditions, with a reduction of up to 40% in arid soils. Temperature fluctuations influence metabolic activities, with optimal growth typically observed between 20–30°C for most microalgae (Ras et al., 2013). However, extreme heat above

40°C can lead to photoinhibition and cellular damage, particularly in exposed soil crusts. Managing these abiotic stressors is essential for leveraging microalgal functions in soil ecosystems.

ii. Nutrient availability

The availability of essential nutrients, including nitrogen, phosphorus, and trace elements, directly impacts the productivity and activity of microalgae in soils. Nutrient-poor soils, common in degraded and arid regions, limit the proliferation of microalgae, reducing their contributions to soil carbon dynamics. Phosphorus deficiency has been identified as a major bottleneck for cyanobacterial growth, as it is required for ATP synthesis and cellular processes (Wei et al., 2023). The competitive uptake of nutrients by other soil microorganisms further restricts the availability of resources for microalgal activity. To address these limitations, targeted nutrient management practices, such as the addition of organic amendments or microalgal inoculants enriched with nutrients, are necessary for optimal performance.

B. Competition with Other Soil Microorganisms

Microalgae face competition from other soil microorganisms, including bacteria, fungi, and archaea, for limited resources such as nutrients, space, and light. This competition can reduce the efficacy of microalgae in contributing to soil carbon sequestration and nutrient cycling. Bacteria, for example, often dominate resource acquisition in nutrient-rich environments, outcompeting microalgae for nitrogen and phosphorus (Cembella et al., 1984). Fungal species, particularly those forming mycorrhizal associations, also influence the distribution and activity of microalgae by altering nutrient availability and soil structure. Moreover, microbial antagonism, such as the production of allelopathic compounds by bacteria, can inhibit microalgal growth, further complicating their integration into soil management practices.

C. Challenges in Large-Scale Application and Cultivation

Scaling up the use of microalgae for agricultural applications presents logistical and economic challenges. Cultivation of microalgae in open systems, such as ponds or bioreactors, requires precise control over environmental conditions, including light, temperature, and nutrient supply, which can be resource-intensive. The cost of producing and harvesting microalgal biomass remains a significant barrier, with estimates ranging from \$5–\$10 per kilogram, depending on the production system and scale (Sun et al., 2011). The transportation and storage of algal inoculants for field application pose practical difficulties, particularly in remote or resource-constrained areas. Ensuring the viability and effectiveness of microalgal biofertilizers under varying soil and climatic conditions further complicates their large-scale adoption. Efforts to address these challenges include the development of cost-effective cultivation technologies, such as low-energy photobioreactors, and the use of wastewater or agricultural runoff as nutrient sources for microalgal growth. Advances in bioprocessing techniques, such as flocculation and centrifugation, are also being explored to reduce production costs and improve scalability.

D. Knowledge Gaps in Long-term Impacts on Soil Health

Despite the promising potential of microalgae in soil management, there are significant knowledge gaps regarding their long-term impacts on soil health and ecosystem functions. While short-term studies have demonstrated improvements in soil fertility and carbon sequestration, the persistence of microalgal biomass and its contributions to stable soil organic carbon pools over decades remain unclear. The potential for unintended ecological consequences, such as shifts in microbial community composition or nutrient imbalances, requires further investigation (Tong et al., 2022). The interactions between microalgae and other soil components, including minerals and organic matter, are not fully understood, limiting the ability to predict their behaviour in complex soil systems. For example, the fate of extracellular polymeric substances (EPS) produced by microalgae and their role in long-term soil aggregation and carbon stabilization remain underexplored.

7. CURRENT RESEARCH AND TECHNOLOGICAL ADVANCEMENTS

A. Advances in Microalgal Isolation and Cultivation Techniques

Significant progress has been made in isolating and cultivating edaphic microalgae for research and agricultural applications. Isolation techniques now employ advanced methods such as flow cytometry, fluorescence-activated cell sorting (FACS), and gradient centrifugation to obtain pure cultures of specific microalgal strains. These approaches allow for the selection of strains with desirable traits such as high carbon fixation capacity, rapid growth, or resilience to environmental stressors. Traditional enrichment culture methods have also been optimized by incorporating selective media and light regimes tailored to specific soil-derived microalgae. Cultivation technologies have expanded from simple open-pond systems to sophisticated photobioreactors that offer better control over environmental parameters such as light intensity, temperature, and nutrient supply. Closed systems such as tubular and flat-plate photobioreactors minimize contamination and water evaporation, making them suitable for large-scale production. Innovations in biofilm-based cultivation systems, where microalgae grow on surfaces rather than in suspension, have demonstrated higher biomass yields and reduced water use, particularly in arid regions (Das et al., 2022). Co-cultivation of microalgae with beneficial bacteria is being explored to enhance nutrient recycling and biomass productivity.

B. Omics Technologies for Genetic and Metabolic Pathways

Omics technologies, including genomics, transcriptomics, proteomics, and metabolomics, have revolutionized the study of microalgae, providing insights into their genetic and metabolic underpinnings. Whole-genome sequencing of soil microalgae such as *Chlorella vulgaris* and *Nostoc* has identified genes involved in photosynthesis, nitrogen fixation, and stress tolerance, paving the way for genetic engineering to enhance these traits (Singh et al., 2023). Transcriptomic analyses under varying environmental conditions have revealed regulatory pathways governing carbon fixation and nutrient metabolism, highlighting potential targets for improving microalgal performance in soil ecosystems. Proteomics studies have elucidated the roles of key enzymes such as ribulose-1,5-bisphosphate carboxylase/ oxygenase (RuBisCO) in carbon assimilation and nitrogenase in nitrogen fixation, providing a molecular basis for optimizing these processes. Metabolomics has identified secondary metabolites produced by microalgae, such as exopolysaccharides and phytohormones, which contribute to soil aggregation and plant growth promotion. These omics-driven insights enable precision bioengineering of microalgae to enhance their functional capabilities, making them more effective in soil carbon sequestration and agricultural applications (Barh et al., 2017).

C. Field Trials and Experimental Studies on Soil Carbon Dynamics

Field trials and experimental studies have provided valuable evidence for the role of microalgae in enhancing soil carbon dynamics and improving soil health. In degraded soils, inoculation with cyanobacteria such as *Microcoleusvaginatus* has been shown to increase soil organic carbon content by 15–30% over two years. Similar studies in agricultural fields have demonstrated that applying *Chlorella vulgaris* as a biofertilizer improves SOC levels and crop yields, with reported yield increases of 10–20% in rice and wheat systems. Controlled experiments have also elucidated the mechanisms through which microalgae contribute to carbon sequestration. Microalgal biofilms have been shown to enhance soil aggregation, reducing carbon losses through erosion by 40–60% in arid environments. Long-term studies are investigating the stability of carbon stored in soil microalgal biomass and its integration into stable soil organic matter fractions. These experimental findings are critical for validating the scalability and sustainability of microalgal technologies in diverse agroecological contexts (Wolf et al., 2023).

D. Integration of Remote Sensing and Modeling in Microalgae Research

Remote sensing and modeling tools are increasingly being employed to monitor and optimize the application of microalgae in soil management and carbon sequestration. Hyperspectral and multispectral imaging techniques allow for the non-invasive detection of microalgal biomass and photosynthetic activity in soil crusts, providing real-time data on their spatial distribution and productivity. These tools are particularly valuable in large-scale applications, where traditional monitoring methods are impractical. Predictive modeling frameworks are being developed to simulate the impact of microalgal inoculation on soil carbon dynamics under various environmental scenarios. For example, process-based models such as the DeNitrification–DeComposition (DNDC) model have been adapted to include microalgal contributions to carbon and nitrogen cycles, enabling more accurate assessments of their long-term effects on soil health and greenhouse gas emissions. Geospatial modeling combined with remote sensing data helps identify suitable regions for microalgal application, considering factors such as soil type, climate, and land use (Chen et al., 2024). These advancements in isolation techniques, omics technologies, field studies, and remote sensing integration underscore the growing potential of microalgae in climate-smart agriculture. Continued innovation and interdisciplinary collaboration are essential to overcoming current limitations and realizing the full benefits of microalgal technologies for sustainable soil management and carbon sequestration.

8. FUTURE AND RESEARCH

A. Developing Cost-effective and Scalable Solutions

The economic feasibility of utilizing microalgae in climate-smart agriculture remains a significant challenge. Current cultivation methods, including photobioreactors and open pond systems, involve high capital and operational costs, with production expenses estimated at $5–$10 per kilogram of biomass. To make microalgae-based solutions viable at scale, future research must focus on cost reduction through technological innovations. Using low-cost materials for bioreactor construction, such as agricultural residues and recycled plastics, has shown promise in reducing initial investment costs. Integrating microalgae cultivation with wastewater treatment facilities offers a dual benefit of reducing production costs and recycling nutrients. Studies have demonstrated that microalgae such as *Chlorella vulgaris* can effectively grow in wastewater, utilizing nitrogen and phosphorus for biomass production while simultaneously cleaning the water (Arsalan & Iqbal, 2023). Advances in harvesting techniques, such as bio flocculation and membrane filtration, have also been explored to minimize energy input during biomass recovery, which remains one of the most resource-intensive steps. Scaling up production using biofilm-based systems has further been identified as a viable approach, with reported increases in biomass yield and reduced water requirements.

B. Exploring Diverse Microalgal Species for Enhanced Functionality

Diversity in microalgal species offers untapped potential for optimizing functionality in soil management and carbon sequestration. Current research focuses heavily on a few model species such as *Chlorella vulgaris* and *Nostoc*, but emerging studies suggest that other species, particularly extremophiles, could be better suited for specific environmental conditions. *Scenedesmus sp.* and *Anabaena sp.* have demonstrated superior tolerance to salinity and high temperatures, making them ideal candidates for arid and saline soils. Bioprospecting efforts are being directed toward identifying species with enhanced photosynthetic efficiency, faster growth rates, and higher exopolysaccharide (EPS) production. High-EPS-producing species, such as *Microcoleusvaginatus*, are particularly valuable for improving soil aggregation and reducing erosion. Genomic and metabolic engineering are also being applied to create synthetic strains with improved carbon fixation capacities, stress resistance, and compatibility with agricultural systems (Zhang et al., 2024). These advancements promise to broaden the range of microalgae applications across diverse agroecological zones.

C. Integrating Microalgae in Multi-functional Agricultural Systems

Future agricultural systems must be multi-functional, addressing productivity, sustainability, and resilience. Microalgae can be integrated into various components of such systems to maximize their benefits. For example, agroforestry systems can use microalgal biofilms to stabilize soil around tree roots and enhance nutrient cycling. Microalgae can be incorporated into aquaponics systems, where they serve as a biofilter for wastewater while producing biomass for use as biofertilizers or animal feed. Microalgae can also play a pivotal role in circular bioeconomies by recycling agricultural waste into valuable products. Co-cultivation systems utilizing crop residues as a nutrient source for microalgae have been shown to enhance biomass production while reducing waste management costs (Das et al., 2022). Integration with renewable energy systems, such as solar-powered photobioreactors, further aligns microalgal applications with sustainability goals. Developing these multi-functional systems requires interdisciplinary collaboration among agronomists, microbiologists, and engineers to optimize resource use and minimize trade-offs.

D. Policy Implications and Incentives for Adoption of Microalgal Technologies

The widespread adoption of microalgae-based technologies in agriculture hinges on supportive policies and incentives. Governments and international organizations must recognize the potential of microalgae in addressing climate change and food security challenges, integrating these solutions into national climate action plans and agricultural development strategies. Financial incentives, such as subsidies for microalgae cultivation systems and tax breaks for farmers adopting microalgal biofertilizers, can encourage early adoption and scale-up (Makepa et al., 2024). Policyshould also prioritize research funding to advance microalgae-based innovations. Public-private partnerships can play a critical role in bridging the gap between laboratory research and field-scale applications. Standardizing regulations for the use of microalgae in agriculture, including safety assessments and environmental impact analyses, will ensure the responsible deployment of these technologies. Educational programs aimed at raising awareness among farmers and stakeholders about the benefits and practicalities of microalgal applications are equally essential for fostering acceptance and adoption.

9. CONCLUSION

The integration of edaphic microalgae into climate-smart agriculture represents a transformative approach to enhancing soil health, mitigating climate change, and ensuring sustainable agricultural productivity. These versatile microorganisms contribute significantly to carbon sequestration, nutrient cycling, and soil stabilization, making them invaluable in addressing global environmental challenges. Despite challenges such as environmental limitations, competition with other soil microorganisms, and high costs of large-scale applications, advances in cultivation techniques, omics technologies, and innovative field practices highlight their potential for scalable solutions. Exploring diverse species, integrating them into multifunctional agricultural systems, and supporting adoption through targeted policies and incentives will be crucial. With continued research, interdisciplinary collaboration, and policy support, edaphic microalgae hold the promise of revolutionizing sustainable agriculture, fostering resilience, and playing a pivotal role in global efforts to combat climate change.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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