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Microalgae Biotechnology as An Agent for Remediation and Improvement of Agricultural Soil Quality: A Systematic Literature Review

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ABSTRACT

Agricultural soils are increasingly affected by contaminant accumulation, nutrient imbalance, and declining biological quality, while environmentally safer remediation strategies remain limited. This study synthesizes scientific evidence on the use of microalgae as biotechnological agents for the remediation and improvement of agricultural soil quality through a systematic literature review approach. A total of 17 eligible articles were selected through PRISMA 2020-based screening and analyzed qualitatively. The synthesis focused on the application forms of microalgae, their reported soil-related functions, and the limitations and future directions emerging from the current evidence base. The reviewed studies indicate that microalgae and microalgal products can contribute to pollutant removal, nutrient recovery, soil amendment, fertilizer substitution, biomass valorization, microbial community modulation, and biological soil improvement in agricultural systems. However, the available evidence remains limited and is still dominated by laboratory-scale, greenhouse, pot-based, and context-specific studies. Overall, microalgae represent promising but still developing biotechnological agents for sustainable soil remediation and quality improvement. Broader field validation, long-term assessment, safety evaluation, and scalability analysis are still needed before wider application in agricultural systems.

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INTRODUCTION

Agricultural soils are increasingly affected by contamination, nutrient imbalance, and declining biological function, largely as a consequence of intensive agricultural practices, excessive agrochemical inputs, and the accumulation of residual pollutants in cultivation systems (Álvarez et al., 2021; Ali et al., 2024). These pressures reduce soil fertility, alter soil physicochemical properties, and disrupt biological processes that are essential for sustaining long-term agricultural productivity (Álvarez et al., 2021; Gonçalves et al., 2023). Therefore, sustainable and biologically based strategies are needed to support soil remediation and improve soil quality in agricultural systems (Ali et al., 2024; Castro et al., 2020).

Microalgae have emerged as promising biotechnological agents because of their capacity to contribute to pollutant removal, nutrient recovery, and soil quality improvement through multiple functional pathways (Ali et al., 2024; Álvarez et al., 2021). Living microalgal biomass can adsorb contaminants through functional groups on the cell surface, whereas processed microalgal products, such as biochar, may improve soil physicochemical properties and reduce metal bioavailability (Hifney et al., 2021; Myung et al., 2024). Several microalgal and cyanobacterial taxa are also involved in phosphorus and nitrogen cycling through nutrient uptake, intracellular storage, and gradual nutrient release, thereby supporting more efficient nutrient management in agricultural systems (Mukherjee et al., 2015; Baldisserotto et al., 2023; Rana et al., 2024).

Recent studies have further shown that microalgal biomass can support agricultural nutrient management and fertilizer substitution. For example, *Chlorella vulgaris* and *Scenedesmus obliquus* cultivated in agricultural drainage water have been evaluated for their fertilizer potential, while other studies have examined the use of microalgae to reduce conventional fertilizer inputs in both hydroponic and soil-based cultivation systems (Alvarenga et al., 2023; Zhang et al., 2024). In addition, microalgae-based biofertilizers have been reported to improve soil fertility and microbial community structure, indicating that their contribution may extend beyond nutrient supply to broader biological soil improvement (Song et al., 2024).

Beyond contaminant removal and nutrient cycling, microalgae may also contribute to the biological improvement of soil. Cyanobacterial biomass rich in exopolysaccharides has been reported to enhance soil aggregation, improve water retention, and support beneficial microbial activity, indicating its potential role as a soil conditioner and biofertilizer component (Do Nascimento et al., 2019; Wang et al., 2018; Bomer & Leverett, 2024). At a broader systems level, microalgae-based applications are also associated with circular bioeconomy approaches, particularly when biomass generated from remediation processes is further used for biofertilizer, bioenergy, or other value-added agricultural inputs (Silva et al., 2022; Rana et al., 2024; Castro et al., 2020).

Despite this growing interest, evidence on the use of microalgae for agricultural soil remediation remains fragmented. Many studies are still conducted under laboratory or controlled conditions, focus on a limited number of commonly studied genera such as Chlorella, Spirulina, and Anabaena, and evaluate microalgal performance in simplified systems rather than in complex agricultural soils (Hifney et al., 2021; Myung et al., 2024; Baldisserotto et al., 2023; Wang et al., 2018). In addition, the available findings are dispersed across different application contexts, including biosorption, nutrient recovery, soil conditioning, biomass valorization, and biofertilizer development. This fragmentation makes it difficult to obtain an integrated understanding of how microalgae function as biotechnological agents for agricultural soil remediation and soil quality improvement (Álvarez et al., 2021; Ali et al., 2024; Gonçalves et al., 2023).

In this review, we synthesize current scientific evidence on the use of microalgae as biotechnological agents for the remediation and improvement of agricultural soil quality. We focus on the reported roles of microalgae in soil-related remediation, the main application forms used in previous studies, and the limitations and research gaps that remain in the current literature. By integrating findings from selected studies, this review provides a focused overview of the potential contribution of microalgae to pollutant reduction, nutrient efficiency, biological soil improvement, and more sustainable agricultural soil management.

This review was guided by three research questions:

RQ1. How have previous studies reported the use of microalgae as biotechnological agents for the remediation and improvement of agricultural soil quality?

RQ2. What remediation-related functions and main application forms of microalgae have been identified in the selected studies?

RQ3. What limitations, knowledge gaps, and future research directions emerge from the current evidence on microalgae-based agricultural soil remediation?

RESEARCH METHODS

This study employed a Systematic Literature Review (SLR) approach to identify, evaluate, and synthesize published studies on the use of microalgae for the remediation and improvement of agricultural soil quality. The review process was guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) framework to ensure a transparent and structured article selection process (Figure 1).

The literature search was conducted using the Scopus database, which was selected because it provides broad coverage of peer-reviewed international publications in environmental science, agricultural systems, and biotechnology. The search focused on studies published between 2020 and 2025 in order to capture recent developments in microalgae-based applications for agricultural soil remediation and soil quality improvement. However, a limited number of earlier studies published before 2020 were retained when they were considered necessary for conceptual support and interpretation of the findings. In addition to Scopus database searching, relevant studies were also identified through other sources, including reference tracking and targeted manual searches of articles closely related to microalgae-based biofertilizers, soil quality improvement, and fertilizer substitution. These additional sources were included when they met the same eligibility criteria and were directly relevant to the scope of the review.

The search strategy used combinations of keywords related to microalgae, agricultural soils, and remediation. The main search terms included "microalgae," "green microalgae," "cyanobacteria," "biosorption," "biochar," "biofertilizer," "agricultural soil remediation," "soil quality," and "soil contamination." These terms were combined using Boolean operators as follows: ("microalgae" OR "green microalgae" OR "cyanobacteria") AND ("biosorption" OR "biochar" OR "biofertilizer" OR "agricultural soil remediation" OR "soil quality" OR "soil contamination"). In general, the search was directed toward studies examining microalgae-based applications in contaminated or degraded agricultural soils, including pollutant removal, nutrient recovery, and soil quality enhancement.

The inclusion criteria were as follows: (1) articles published in English; (2) original research articles published in peer-reviewed international journals indexed in Scopus; (3) studies directly relevant to the use of microalgae or cyanobacteria in the remediation or improvement of agricultural soil quality; and (4) studies published between 2020 and 2025. The exclusion criteria included: (1) review articles, book chapters, conference papers, and other non-research documents; (2) studies not directly related to agricultural soils; (3) studies focused exclusively on aquatic or industrial wastewater systems without clear relevance to agricultural soil application; and (4) articles with inaccessible full text.

The article selection process was conducted in several stages. First, potentially relevant studies were identified through database searching. Second, titles, abstracts, and keywords were screened to assess thematic relevance. Third, the full texts of potentially eligible articles were examined using the predefined inclusion and exclusion criteria. The final selection yielded 17 articles that were considered sufficiently relevant for focused qualitative synthesis.

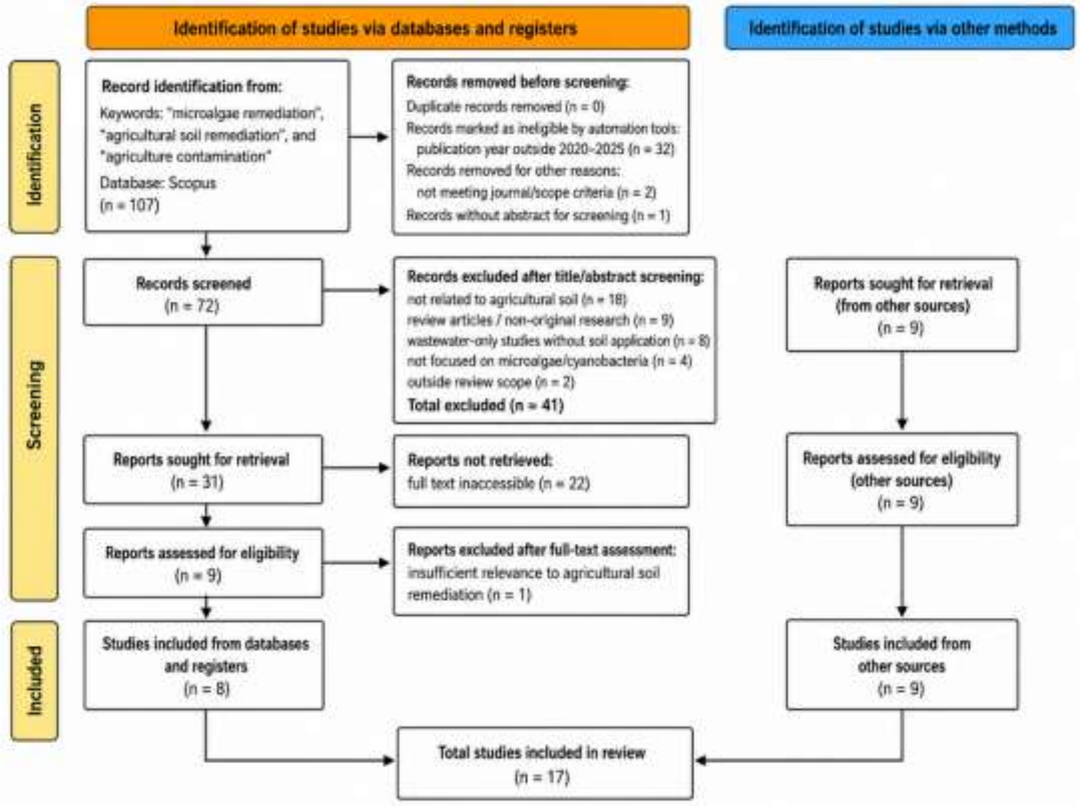

Figure 1. Flowchart of the PRISMA Selection Process for Microalgae Biotechnology as an Agent for Remediation and Improvement of Agricultural Soil Quality

Data from the selected studies were extracted using a structured review matrix. The extracted information included author and year of publication, microalgal species or biomass type, study objective, application context or test medium, soil-related parameters assessed, principal findings, and reported limitations. The selected studies were then compared and synthesized qualitatively, with emphasis on the remediation-related roles of microalgae, the main forms of application used, and the recurring limitations identified across studies.

Because the number of eligible studies was limited and the selected articles showed substantial variation in design, application context, and measured parameters, this review was intended as a focused qualitative synthesis rather than a quantitative meta-analysis. Therefore, the findings were interpreted cautiously, with greater emphasis on recurring patterns across studies and on the identification of knowledge gaps and future research needs. This approach was adopted to ensure that the conclusions remained proportional to the available evidence base.

RESEARCH RESULT

Based on the final selection process, 17 articles were included in this review for qualitative synthesis. Overall, the selected studies reported the use of microalgae or cyanobacteria in several agricultural soil-related contexts, including pollutant removal, nutrient recovery, soil amendment, fertilizer substitution, soil conditioning, biomass valorization, and biological enhancement. The reviewed studies involved different application forms, including living microalgal biomass, cyanobacterial inoculum, microalgal biochar, microalgae-based biofertilizer, wastewater-grown microalgal biomass, and microalgae–microbial consortia. Commonly studied genera included *Chlorella, Scenedesmus, Desmodesmus, Spirulina, Nostoc, Anabaena, Tribonema*, and nitrogen-fixing cyanobacteria. The reviewed evidence indicates that microalgae have been investigated not only for their ability to reduce contaminants or recover nutrients, but also for their potential contribution to soil fertility, crop performance, microbial community structure, organic matter improvement, and circular agricultural resource management.

RQ1. Use of Microalgae as Biotechnological Agents for Agricultural Soil Remediation and Soil Quality Improvement

The selected studies show that microalgae have been used in different forms and application contexts as biotechnological agents for the remediation and improvement of agricultural soil quality (Table 1). In several studies, living microalgal biomass was applied because of its biosorption capacity, metabolic activity, and ability to remove organic pollutants or excess nutrients from nutrient-rich media (Hifney et al., 2021; Baldisserotto et al., 2023; Rana et al., 2024; Palikrousis et al., 2024). Other studies used processed biomass, such as microalgal biochar, to improve soil physicochemical properties and reduce the bioavailability of heavy metals in agricultural soils (Myung et al., 2024).

A second group of studies examined microalgae and cyanobacteria as agricultural inputs for nutrient recycling, fertilizer substitution, and soil fertility improvement. For example, *Chlorella vulgaris* and *Scenedesmus obliquus* cultivated in agricultural drainage water were evaluated as liquid organic fertilizers, while microalgae-based treatments were also tested as partial substitutes for conventional fertilizers in both hydroponic and soil-based cultivation systems (Alvarenga et al., 2023; Zhang et al., 2024). Similarly, wastewater-grown microalgal biomass was examined as a nutrient source for crop production, supporting the potential use of microalgae in circular bioeconomy-oriented agricultural systems (Álvarez-González et al., 2022).

A third group of studies focused on the role of microalgae and cyanobacteria in soil biological enhancement. Cyanobacterial biomass and inoculum were reported to support soil conditioning, aggregation, water retention, microbial activity, crop-related performance, and soil carbon sequestration (Do Nascimento et al., 2019; Wang et al., 2018; Uniyal et al., 2024; Li et al., 2025). More recent studies also showed that microalgae-based biofertilizers can influence soil fertility and microbial community structure, suggesting that their contribution may extend beyond nutrient supply to broader biological soil improvement (Song et al., 2024; Su et al., 2025).

Overall, these studies indicate that microalgae have been investigated not only for contaminant removal and nutrient recovery, but also for their contributions to soil fertility, crop performance, microbial community structure, organic matter improvement, and circular agricultural resource management.

Table 1. Characteristics of the Selected Studies on Microalgae-Based Remediation and Agricultural Soil Quality Improvement

Author & Year	Microalgal species/ biomass type	Study objective	Application (Main parameters assessed)	Main findings	Reported limitations
Hifney et al. (2021)	*Chlorella* sp.	To evaluate the biosorption potential of living microalgae for pharmaceutical pollutant removal	Contaminant solution (Ketoprofen, diclofenac, adsorption efficiency, pH)	Living *Chlorella* sp. showed effective biosorption of ketoprofen and diclofenac under suitable pH conditions	Conducted in controlled conditions and not directly tested in agricultural soil
Myung et al. (2024)	*Spirulina platensis* biochar	To assess microalgal biochar for heavy metal adsorption and soil physicochemical improvement	Agricultural soil (Pb, Zn, soil pH, cation exchange capacity)	Biochar reduced Pb and Zn and improved soil physicochemical properties	Not evaluated under long-term field conditions
Baldisserotto et al. (2023)	Native *Chlorella*-like strain-based biomass	To investigate nutrient removal efficiency and biomass performance in phytoremediation	Urban wastewater centrate stream (Phosphorus, nitrogen, morphophysiology,	The *Chlorella* strain showed promising nutrient removal capacity and biomass	Conducted in aqueous waste medium rather than direct

Author & Year	Microalgal species/ biomass type	Study objective	Application (Main parameters assessed)	Main findings	Reported limitations
			nutrient removal efficiency)	potential for reuse	agricultural soil application
Rana et al. (2024)	*Chlorella* sp. S5	To evaluate agricultural runoff remediation and sustainable biofuel production in an integrated biorefinery system	Agricultural runoff / nutrient-rich medium (Nitrate, phosphate, biomass production)	The system achieved nutrient removal while generating biomass with biorefinery potential	Laboratory-based and requires broader application validation
Bomer & Leverett (2024)	*Desmodesmus* XB and *Desmodesmus* AxB	To examine growth characteristics and short-term effects on soil microbial dynamics	Soil system (Soil microbial dynamics, biological responses)	Microalgal application influenced short-term soil microbial activity	Short-term study with limited evidence for long-term soil outcomes
Palikrousis et al. (2024)	*Chlorella sorokiniana*	To examine the effect of light intensity on growth and nutrient uptake	Biogas plant digestate (Growth, nutrient uptake, light intensity response)	*C. sorokiniana* showed nutrient uptake potential under controlled cultivation conditions	Focused on digestate cultivation rather than direct soil remediation
Uniyal et al. (2024)	*Nostoc sp.* HNBGU 006, *Pseudanabaena biceps, Chroococcus turgidus*	To assess the effects of cyanobacterial inoculation on crop yield and quality	Agricultural crop system (Allium sativum) (Yield, quality, agronomic response)	*Nostoc* inoculation showed beneficial effects on crop-related performance	Agricultural benefit shown in a specific crop system; broader soil remediation application remains limited
Silva et al. (2022)	Microalgal biomass from food agro-industrial effluent	To evaluate the agricultural potential of microalgal biomass through a life cycle approach	Agricultural crop system (Allium sativum) (Agriculture / life cycle assessment context) (Environmental footprint, renewable resource potential)	Microalgal biomass showed potential as a renewable agricultural resource with environmental benefits	Indirect evidence; not a direct soil remediation trial

Author & Year	Microalgal species/ biomass type	Study objective	Application (Main parameters assessed)	Main findings	Reported limitations
Maurya et al. (2025)	Cyanobacteria–bacteria consortia	To evaluate the enhancement of soil fertility using microbial consortia	Soil fertility system (Soil fertility indicators)	Cyanobacteria–bacteria consortia improved soil fertility-related parameters	Requires further validation under wider agricultural conditions
Li, T. et al. (2025)	Soil green alga *Desmochloris* sp. FACHB-3271	To investigate physiological and transcriptomic responses to salt stress	Stress-response / degraded soil relevance (Salt stress response, physiological and transcriptomic indicators)	The alga showed adaptive responses to salinity stress, indicating relevance for stressed or degraded soils	Focused on stress tolerance rather than direct remediation performance
Li, S. et al. (2025)	*Anabaena azotica* SJ-1	To evaluate rice production and soil carbon sequestration improvement	Agricultural soil / rice production system (Rice production, soil carbon sequestration)	Nitrogen-fixing cyanobacteria improved rice production and contributed to soil carbon sequestration	Application needs broader testing under diverse field conditions
Alvarenga et al. (2023)	*Chlorella vulgaris* and *Scenedesmus obliquus*	To evaluate the fertilizer potential of microalgae cultivated in agricultural drainage water	Agricultural drainage water and crop cultivation system; fertilizer potential, soil electrical conductivity, crop response	Microalgal biomass showed potential as a liquid organic slow-release fertilizer and may reduce the risk of secondary soil salinization	Application was evaluated under specific crop and cultivation conditions; broader field validation is needed
Álvarez-González et al. (2022)	Wastewater-grown microalgal biomass	To evaluate whether microalgae grown in wastewater can reduce the use of inorganic fertilizers	Basil crop system; plant growth, nutrient supply, fertilizer substitution	Combining microalgae-based fertilizer with inorganic fertilizer showed potential as a nutrient source for crop production	Microalgae alone did not consistently outperform inorganic fertilizer; optimization of dose and combination strategy is needed
Zhang et al. (2024)	*Chlorella* sp. and *Anabaena* sp.	To examine the use of microalgae to reduce conventional fertilizer input	Hydroponic and soil-based cultivation; crop yield, quality, fertilizer reduction	Microalgae showed potential to reduce conventional fertilizer use, especially when	Performance may depend on crop type, fertilizer combination, and

Author & Year	Microalgal species/ biomass type	Study objective	Application (Main parameters assessed)	Main findings	Reported limitations
				combined with organic fertilizer	cultivation system
Castro et al. (2024)	Microalgal biomass before and after anaerobic digestion or co-digestion with food waste	To evaluate microalgal biomass as agricultural fertilizer before and after anaerobic treatment	Soil and plant system; biofertilizer effect, soil and plant response	Microalgal biomass showed potential for valorization as a biofertilizer and nutrient source	Requires further evaluation of long-term soil effects, safety, and scalability
Song et al. (2024)	*Tribonema* sp.	To assess effects of microalgae-based biofertilizer on soil fertility and microbial community structure	Potted tomato soil; soil nutrients, bacterial and fungal community structure	Microalgae-based biofertilizer improved soil fertility indicators and altered microbial community structure	Conducted in a pot system; field-scale and long-term validation are still needed
Su et al. (2025)	Microalgae and microbial inoculant	To evaluate the effect of partial chemical fertilizer substitution on crop yield, quality, and soil microorganisms	*Polygala tenuifolia* cultivation; soil properties, microbial community, yield and quality	Partial substitution of chemical fertilizer with microalgae and microbial inoculant improved soil properties, microorganisms, and crop performance	Findings are crop-specific; broader testing across soils and crops is required

RQ2. Remediation-Related Functions and Main Application Forms of Microalgae

The selected studies indicate that the remediation-related functions of microalgae are closely associated with the form in which the biomass is applied. Living microalgal biomass was most frequently linked to biosorption, nutrient uptake, and biological interactions within the growth medium or soil system. For example, living *Chlorella* sp. was reported to adsorb pharmaceutical contaminants, while other microalgal systems showed the ability to remove excess nitrogen and phosphorus from nutrient-rich media, including wastewater centrate, agricultural runoff, and digestate (Hifney et al., 2021; Baldisserotto et al., 2023; Rana et al., 2024; Palikrousis et al., 2024).

These findings suggest that living biomass is particularly relevant for active remediation processes involving pollutant reduction and nutrient recovery.

Processed microalgal biomass was more commonly associated with soil amendment and contaminant immobilization. The clearest example is the use of Spirulina platensis biochar, which was reported to adsorb Pb and Zn while improving soil pH and cation exchange capacity, indicating that processed microalgal biomass may serve not only as a sorbent but also as a soil-quality-enhancing material (Myung et al., 2024). In addition, microalgal biomass generated from food agro-industrial effluent or wastewater treatment systems has been evaluated as a renewable agricultural resource, supporting the link between remediation, biomass valorization, and circular bioeconomy approaches (Silva et al., 2022; Álvarez-González et al., 2022; Castro et al., 2024).

Inoculum-based and consortium-based applications were more closely related to soil fertility improvement and biological enhancement. Cyanobacterial inoculation, such as *Nostoc* sp. and nitrogen-fixing cyanobacteria, was associated with improved crop-related performance, soil fertility, and carbon sequestration (Uniyal et al., 2024; Li et al., 2025). Cyanobacteria–bacteria consortia also showed potential for improving soil fertility-related parameters (Maurya et al., 2025). In addition, microalgae-based biofertilizers and microalgae–microbial inoculant combinations were associated with improved soil properties, microbial community structure, and crop performance (Song et al., 2024; Su et al., 2025).

Taken together, the reviewed studies show that microalgae can contribute to agricultural soil remediation and quality improvement through multiple pathways, including pollutant removal, nutrient recovery, soil amendment, fertilizer substitution, biomass valorization, and biological enhancement. However, the specific function observed in each study was strongly influenced by the application form, environmental context, and target parameter assessed. This indicates that microalgae are best understood as flexible biological resources whose effects depend on how they are cultivated, processed, and integrated into agricultural management systems.

RQ3. Limitations, Knowledge Gaps, and Future Research Directions

Despite the promising findings reported in the selected studies, several limitations were consistently identified across the current body of evidence. First, many studies were conducted under laboratory, greenhouse, or controlled cultivation conditions, which limits direct extrapolation to field-scale agricultural systems. Although several recent studies have begun to examine soil-based cultivation, potted crop systems, or partial fertilizer substitution, long-term field validation remains limited.

Second, the evidence remains concentrated on a relatively small number of commonly studied genera, particularly *Chlorella*, *Scenedesmus*, *Spirulina*, *Nostoc*, and *Anabaena*. The performance of other locally adapted or stress-tolerant microalgae remains insufficiently explored, especially under diverse soil types, climatic conditions, and contaminant pressures. This gap is important because the effectiveness of microalgae-based remediation and biofertilization may depend strongly on strain identity, environmental tolerance, and compatibility with local soil conditions.

Third, the reviewed studies used varied application contexts, test media, target parameters, and evaluation methods. Some studies focused on contaminant removal or nutrient recovery, whereas others examined crop growth, soil physicochemical properties, microbial community structure, carbon sequestration, or biomass valorization. This diversity shows the multifunctional potential of microalgae, but it also makes direct comparison across studies difficult. Standardized indicators are still needed to evaluate microalgae-based soil remediation in a more comparable way.

Another important gap concerns the limited integration of remediation performance with long-term agricultural outcomes. While many studies reported positive effects on pollutant reduction, nutrient recovery, soil fertility, or selected crop parameters, fewer studies evaluated whether these improvements were maintained over time or translated into sustained soil health, stable crop productivity, and practical field-level benefits. In addition, although several studies highlighted circular bioeconomy potential, the economic feasibility, scalability, and safety of applying microalgal biomass derived from wastewater or waste streams require further evaluation.

These limitations indicate that future research should move beyond short-term proof-of-concept studies toward more field-relevant and application-oriented investigations. Further work is needed to evaluate microalgal performance under diverse agricultural soil conditions, compare different biomass forms and application strategies, and assess both remediation effectiveness and longer-term soil-quality outcomes. Greater attention should also be given to locally adapted strains, microbial consortia, field-scale validation, environmental safety, cost-effectiveness, and integration with sustainable agricultural management and circular bioeconomy approaches.

DISCUSSION

The findings of this review indicate that microalgae and cyanobacteria have broad potential as biotechnological agents for the remediation and improvement of agricultural soil quality. Across the 17 selected studies, microalgae were associated with several soil-related functions, including pollutant removal, nutrient recovery, soil amendment, fertilizer substitution, biomass valorization, microbial community modulation, and biological soil improvement. These findings suggest that microalgae should not be viewed only as agents for contaminant removal. Rather, they represent multifunctional biological resources that may support several interconnected aspects of soil quality and sustainable agricultural management. This interpretation is consistent with previous literature highlighting the potential of microalgae in agricultural, environmental, and circular bioeconomy applications (Álvarez et al., 2021; Gonçalves et al., 2023; Song et al., 2022).

A consistent pattern emerging from the reviewed studies is that the function of microalgae depends strongly on the form in which they are applied. Living microalgal biomass was generally associated with active biosorption, nutrient uptake, and biological interactions within the growth medium or soil system. This pattern was observed in studies involving *Chlorella* sp., *Desmodesmus* sp., and other living algal systems, which were mainly linked to pollutant adsorption, nitrogen and phosphorus removal, and short-term effects on soil microbial dynamics (Hifney et al., 2021; Baldisserotto et al., 2023; Bomer & Leverett, 2024; Palikrousis et al., 2024). Studies using microalgae cultivated in agricultural drainage water or wastewater further indicate that nutrient recovery can be connected with subsequent agricultural use, particularly when the resulting biomass or algal suspension is applied as a biofertilizer or partial nutrient source (Álvarez-González et al., 2022; Alvarenga et al., 2023). Thus, living microalgal systems may contribute not only to remediation during cultivation, but also to nutrient recycling after biomass recovery.

Processed microalgal biomass was more closely related to soil amendment, contaminant immobilization, and nutrient valorization. For example, *Spirulina platensis* biochar was reported to reduce Pb and Zn availability while improving soil physicochemical properties, indicating its potential as both a sorbent and a soil-quality-enhancing material (Myung et al., 2024). Similarly, fresh, digested, or co-digested microalgal biomass derived from waste-treatment systems has been evaluated as a biofertilizer and soil conditioner, with potential benefits for soil organic matter, nitrogen, phosphorus, and plant growth responses (Castro et al., 2024). These findings show that the processing route is an important determinant of microalgal function. Living biomass appears more suitable for active nutrient uptake and biosorption, whereas processed biomass may be more appropriate for soil amendment, slow nutrient release, and contaminant immobilization.

Inoculum-based and consortium-based applications were more closely associated with soil fertility enhancement, crop-supporting functions, and biological soil improvement. Cyanobacterial inoculation, including *Nostoc* sp. and nitrogen-fixing cyanobacteria, was associated with improved crop-related performance, soil fertility, and soil carbon sequestration (Uniyal et al., 2024; Li et al., 2025). Cyanobacteria–bacteria consortia also showed potential for enhancing soil fertility-related parameters (Maurya et al., 2025). More recent studies further support this pattern by showing that microalgae-based biofertilizers and microalgae–microbial inoculant combinations can influence soil nutrients, microbial community structure, crop yield, and crop quality (Song et al., 2024; Su et al., 2025). These findings suggest that the contribution of microalgae to agricultural soil improvement may extend beyond nutrient supply to include biological regulation of the rhizosphere and soil microbial environment.

Evidence on fertilizer substitution further expands the practical relevance of microalgae-based applications. Studies on microalgal biomass used in hydroponic and soil-based cultivation suggest that microalgae can reduce reliance on conventional fertilizers, especially when combined with organic or inorganic nutrient sources (Zhang et al., 2024). Similarly, wastewater-grown microalgae and microalgae cultivated in agricultural drainage water demonstrate a potential pathway for recovering nutrients from waste streams and reusing them in crop production (Álvarez-González et al., 2022; Alvarenga et al., 2023). This supports the view that microalgae-based strategies are not limited to remediation alone, but may also contribute to circular agricultural systems by linking waste treatment, nutrient recovery, biomass production, and soil quality improvement.

In the specific context of heavy metal remediation, microalgae may contribute through several complementary mechanisms, including surface adsorption, ion exchange, EPS-mediated binding, intracellular bioaccumulation, vacuolar sequestration, and intracellular transformation of metal contaminants, as summarized in Figure 2. However, the reviewed evidence indicates that heavy metal remediation represents only one part of a broader functional spectrum. Microalgae may also improve agricultural soil systems through nutrient cycling, organic matter input, microbial stimulation, and crop-supporting effects. Therefore, assessments of microalgae-based soil remediation should integrate both contaminant-focused and soil-quality-focused perspectives.

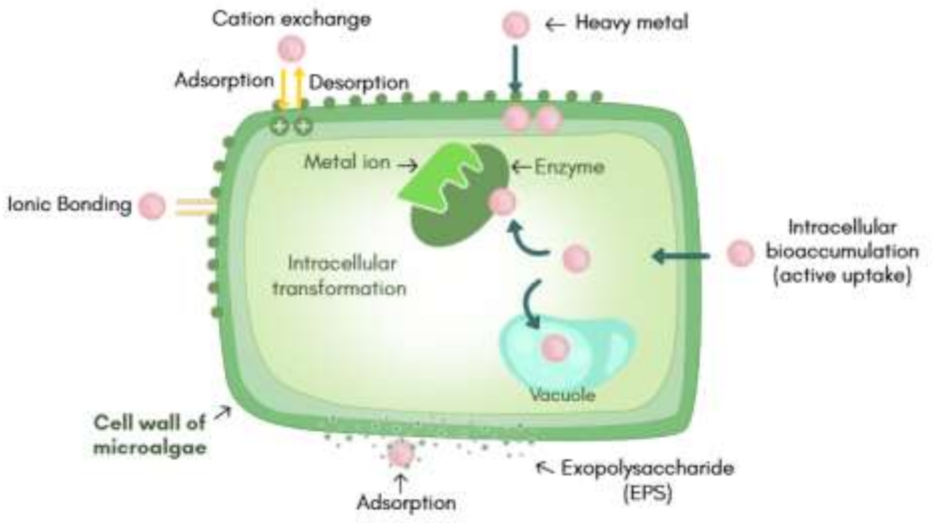

Figure 2. Conceptual illustration of the main mechanisms involved in heavy metal remediation by microalgae

Despite these promising findings, several limitations remain. Although the inclusion of additional studies strengthens the evidence base, many studies were still conducted under laboratory, greenhouse, pot, or otherwise controlled conditions. This limits the direct transfer of findings to field-scale agricultural systems. Several studies also focused on specific crops, such as basil, lettuce, tomato, garlic, *Brachiaria*, or *Polygala tenuifolia*, which means that their findings may not be directly generalizable across different crops, soil types, and climatic conditions (Álvarez-González et al., 2022; Alvarenga et al., 2023; Castro et al., 2024; Song et al., 2024; Su et al., 2025). Therefore, although the current evidence is encouraging, it remains largely context-dependent.

Another important limitation concerns the diversity of microalgal taxa and application strategies. The reviewed studies remain concentrated on a relatively limited number of genera, including *Chlorella*, *Scenedesmus*, *Desmodesmus*, *Spirulina*, *Nostoc*, *Anabaena*, and several nitrogen-fixing cyanobacteria. The performance of other locally adapted, stress-tolerant, or soil-native microalgal strains remains insufficiently explored. This is important because microalgal effectiveness may depend strongly on strain identity, environmental tolerance, growth characteristics, biomass composition, and compatibility with local soil microbial communities. In addition, differences in study design, application dose, biomass form, target parameter, and evaluation period make direct comparison across studies difficult.

The integration between remediation outcomes and long-term agricultural performance also remains limited. Many studies reported positive effects on pollutant reduction, nutrient recovery, soil fertility, crop growth, or microbial community structure. However, fewer studies examined whether these effects were maintained over time or translated into stable improvements in soil health, crop productivity, and farm-level feasibility. In particular, the use of microalgal biomass derived from wastewater, agricultural drainage water, or organic waste-treatment systems requires further assessment of safety, contaminant carryover, nutrient release dynamics, economic feasibility, and farmer-level applicability. These issues are critical before microalgae-based inputs can be recommended for broader agricultural use.

Based on the reviewed evidence, future research should move toward more field-relevant and application-oriented studies. Greater attention is needed to evaluate microalgal performance under diverse agricultural soil conditions, compare different biomass forms and application strategies, and determine which approaches are most suitable for specific soil constraints such as heavy metal contamination, nutrient imbalance, salinity, low organic matter, or declining biological quality. Future studies should also assess locally adapted strains, microbial consortia, long-term soil responses, environmental safety, cost-effectiveness, and scalability. In this respect, microalgae appear promising as multifunctional agents for agricultural soil remediation and quality improvement, but their practical role will depend on stronger field validation and better integration into sustainable land management and circular bioeconomy systems.

CONCLUSION

This systematic literature review indicates that microalgae have promising potential as biotechnological agents for the remediation and improvement of agricultural soil quality. Across the 17 selected studies, microalgae and cyanobacteria were associated with several soil-related functions, including pollutant removal, nutrient recovery, soil amendment, fertilizer substitution, biomass valorization, microbial community modulation, and biological soil improvement. These findings suggest that microalgae may contribute to sustainable agricultural systems not only by reducing environmental stressors, but also by supporting soil fertility, nutrient efficiency, biological activity, and circular resource management.

However, the current evidence base remains limited and is still dominated by laboratory-scale, greenhouse, pot-based, or context-specific studies. Variability in microalgal species, application form, study design, target parameters, and evaluation period also makes direct comparison across studies difficult. Therefore, although the reviewed studies show encouraging results, further research is needed to validate the performance of microalgae under field conditions, assess long-term effects on soil health and crop productivity, and determine the most effective application strategies for different soil constraints. Overall, microalgae represent a promising but still developing approach in agricultural soil remediation and quality improvement, with future progress depending on stronger field-based evidence, safety assessment, scalability evaluation, and better integration into sustainable land management and circular bioeconomy systems.

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