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A Comprehensive Review on Enhancing Saline Soil Reclamation Efficiency through Bacterial Solubilization of Low-Rank Coal

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Abstract

This comprehensive review thoroughly examines soil salinity as a significant agricultural challenge stemming from both natural and human factors. It delves into a wide array of literature to elucidate the emergence of soil salinity as a prevalent issue, offering detailed insights into mitigation strategies and providing an overview of the current soil salinity status and management techniques. The adverse effects of saline conditions on soil health, agricultural output, and ecosystem stability are clearly outlined. This review particularly emphasizes the role of low-rank coal (LRC) and coal-solubilizing bacteria in holistic remediation strategies. Recent advancements in LRC bacterial solubilization offer a sustainable solution for reclaiming saline soils, improving soil quality, and fostering microbial activity. Furthermore, the review aims to analyze recent studies on the bacterial solubilization of LRC, highlighting its potential in bioremediation, resource recovery, and sustainable agriculture practices. Overall, this comprehensive review significantly contributes to existing knowledge by detailing recent advancements in LRC solubilization by bacteria, demonstrating its potential for environmental restoration, soil revitalization, and crop production, and emphasizing its broader applications across various industries, thus paving the way for eco-friendly solutions and sustainable growth.

Keywords: Low-rank coal; Bacteria; Solubilization; Saline soil; Humified organic matter.
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1. Introduction

Soil salinity, a widespread agricultural issue, arises from various natural and anthropogenic factors, leading to detrimental impacts on soil health, agricultural productivity, and ecosystem sustainability.[1] Natural causes include geological processes, such as the weathering of rocks and minerals, which release salt into the soil.[2] Arid and semi-arid climates, accompanied by low rainfall and high evaporation rates, exacerbate salt accumulation due to insufficient leaching.[3] Moreover, human activities contribute substantially to soil salinization. Improper irrigation practices, particularly excessive or inefficient water usage without adequate drainage, result in the accumulation of salts as water evaporates, leaving behind concentrated saline residues.[4] Irrigation with poor-quality water containing high salt concentrations further exacerbates this issue, gradually deteriorating soil quality. The damaging effects of soil salinity are multifaceted. Salts hinder water absorption by plants, causing osmotic stress, reduced nutrient uptake, and inhibited growth.[5] High soil salinity adversely impacts soil structure, diminishes soil porosity, and disrupts microbial communities, which are vital for nutrient cycling. Consequently, agricultural yields plummet, rendering previously fertile lands unproductive.[6] Ecosystem services also suffer, as salinization can contaminate groundwater and downstream water bodies, affecting aquatic life and human water resources. Addressing soil salinity necessitates holistic approaches that incorporate improved irrigation management, efficient water use, soil amendments, and crop selection for salt tolerance.[7]

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Combining sustainable agricultural practices with innovative technologies remains crucial to mitigate the detrimental impacts of soil salinity and safeguard global food security while preserving environmental integrity.[8]

Low-rank coal (LRC) can play a pivotal role in the reclamation of saline soils due to its potential as an organic amendment.[9] When solubilized by bacterial action, LRC produces humified organic matter (HOM), which can significantly improve soil quality in saline-affected areas.[10] LRC acts as a natural source of organic carbon, fostering microbial activity and enhancing soil fertility.[11] HOM derived from coal contains compounds that promote soil aggregation, increase water retention capacity, and improve soil structure. These amendments help reduce soil salinity by promoting excess salt and ion leaching, thereby restoring soil health and productivity. Furthermore, the microbial activity induced by solubilized coal promotes the degradation of toxic compounds and aids pollutant breakdown, contributing to soil remediation efforts in saline environments. Solubilized LRC as an organic amendment presents an eco-friendly and sustainable approach to improving saline soils. This approach addresses soil degradation and offers a cost-effective and environmentally conscious method for rehabilitating and reclaiming these landscapes, thus supporting agricultural productivity and ecosystem restoration (Fig. 1).[12]

This review aims to analyze the benefits of LRC solubilization by different bacterial species based on recent studies.[13] By examining the diverse abilities of various bacteria in breaking down LRC, the review aims to uncover the potential for bioremediation, resource recovery, and sustainable energy production.[14] Recent research has highlighted the enzymatic capabilities of specific bacterial species, highlighting their capacity to degrade complex organic compounds within LRC, leading to enhanced solubilization.[15] The analysis seeks to summarize and evaluate the collective findings, shedding light on the promising applications of bacterial solubilization in diverse fields, such as environmental remediation, bioenergy, and industrial processes.[16]

2. Factors contributing to soil salinity and their resulting detrimental effects

Soil is a finite and irreplaceable resource, and its depletion is irreversible throughout human lifespan. Soil salinity is ranked as the second leading cause of land degradation following soil erosion and has posed a persistent challenge to agricultural societies for over 10,000 years.[17] On a global scale, approximately 2,000 ha of arable land is relinquished from agricultural production daily due to the encroachment of salinization. The consequences of this phenomenon are noteworthy, as salinization can reduce crop yield by 10% – 25% across a broad spectrum of crops. In severe cases, it can render land unsuitable for cultivation entirely, paving the way for desertification.[18]

Effectively addressing soil salinization requires the implementation of enhanced practices encompassing soil, water, and crop management. This transformation becomes an imperative endeavor not only to ensure food security but also to avert the progression of desertification. The adverse impacts of soil salinity on crop productivity, when left unmitigated, can jeopardize global food supplies and intensify the already pressing challenges of feeding a growing global population.[19] Considering the profound and far-reaching effects of soil salinization, proactive measures to combat this issue are crucial for sustainable land management.[20] It entails strategies that not only rehabilitate salt-affected soils but also prevent further salinization. By advancing our knowledge of the underlying causes and mechanisms of salinization and implementing sustainable practices, we can enhance the

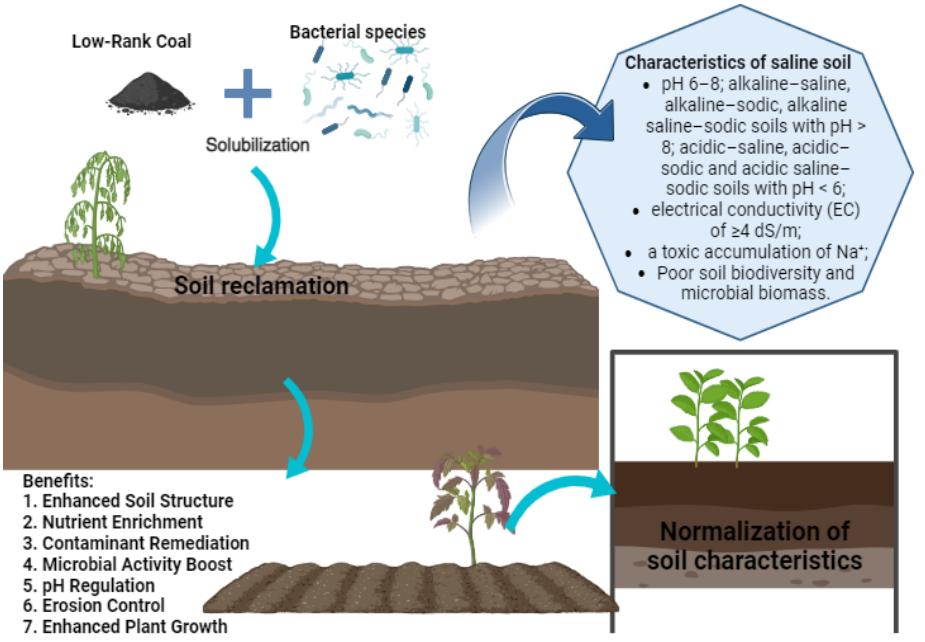

Fig. 1 Normalization of soil characteristics by LRC solubilization.

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resilience of agricultural systems and mitigate the longstanding impacts of soil salinity on human societies and ecosystems. In this context, a comprehensive approach to managing soil salinity is essential for securing our food supply and averting desertification's encroachment.[21]

Soil salinity, a common issue affecting agricultural productivity, stems from various sources. The causes of salt salinization in soils are diverse and multifaceted. Among these origins, inherent soil salinity remains fundamental, initiated by the natural weathering of rocks and the composition of the parent material.[21-24] The major causes of soil salinity include natural factors like inherent soil salinity resulting from the weathering of rocks and parent material, as well as human-induced factors such as the use of brackish and saline irrigation water. Additionally, coastal vulnerability plays a significant role, with overutilization leading to the infiltration of seawater into aquifers (Fig. 2).

Soil salinity is a critical concern that impacts agricultural productivity and ecological balance, stemming from a combination of natural and human-induced factors. Understanding these diverse causes is crucial for developing effective prevention and mitigation strategies. Inherent soil salinity, originating from rock weathering and parent materials, releases salts into the soil, thereby establishing initial salinity levels in certain regions. Additionally, saline irrigation water accelerates salt accumulation as water evaporates, leaving behind concentrated salts. Coastal regions face unique challenges due to excessive freshwater extraction, which leads to seawater infiltration into aquifers and soil, and compromises fertility. Poor drainage and rising water tables cause waterlogging and salt buildup, whereas natural processes like surface evaporation and plant transpiration concentrate salt in soil. Furthermore, marine-derived precipitation and wind-driven salinity contribute to coastal salt accumulation and high-salinity areas, respectively. Human practices intensify soil salinity through fertilizer overuse, indiscriminate additive use, and sewage sludge or industrial brine disposal, impacting salt distribution. Holistic approaches to sustainable agriculture, water management, and soil conservation are essential for mitigation.[24,25]

Widespread use of brackish and saline irrigation water in farming introduces salts, intensifying soil salinity.[25] Coastal regions suffer from seawater intrusion due to excessive freshwater extraction, elevating salinity in both land and aquifers. Environmental factors like poor drainage and rising water tables worsen soil salinity. Natural processes such as surface evaporation, plant transpiration, seawater sprays, and condensed vapors contribute to rising salt content.[26] Additionally, sewage sludge, treated effluent, and industrial brine disposal on soil surfaces exacerbate this challenge. Overall, soil salinity results from a complex interplay between natural processes and human activities, which necessitates comprehensive strategies for sustainable agriculture and environmental preservation.

In a hypothetical soil salinization cycle, the process typically starts with introducing salts from various sources into the soil (Fig. 3).[27-30] Natural factors such as weathering of rocks, compounded by human activities like irrigation with

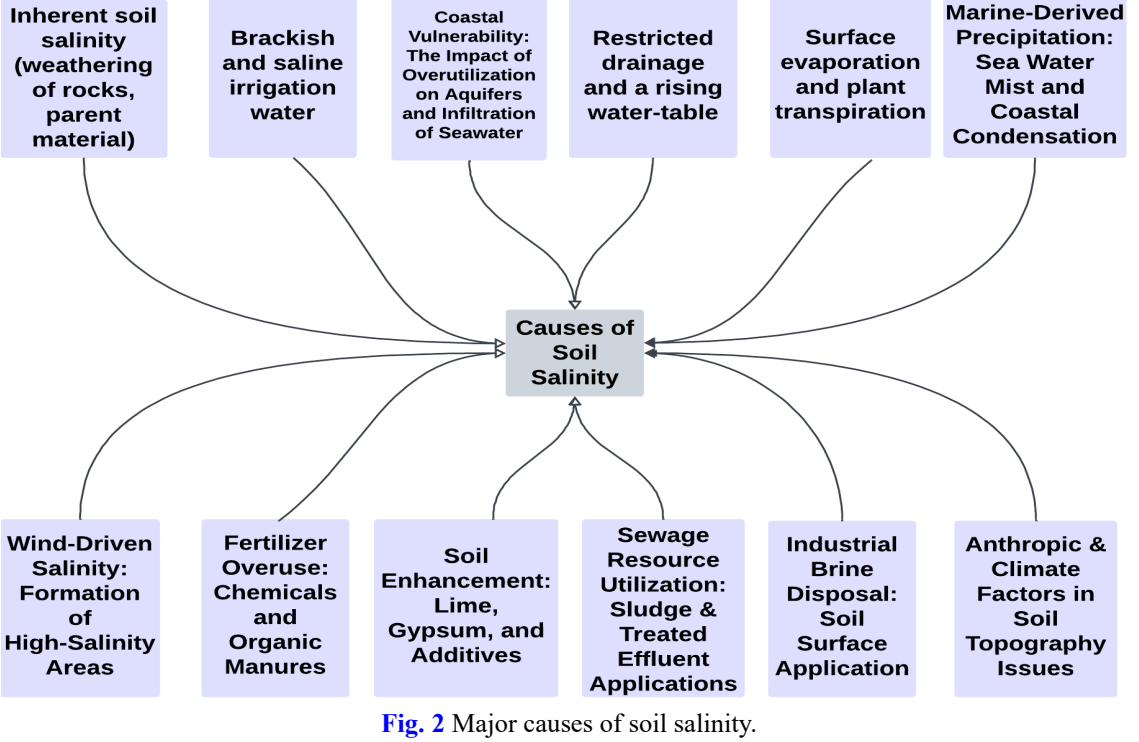

Fig. 2 Major causes of soil salinity.

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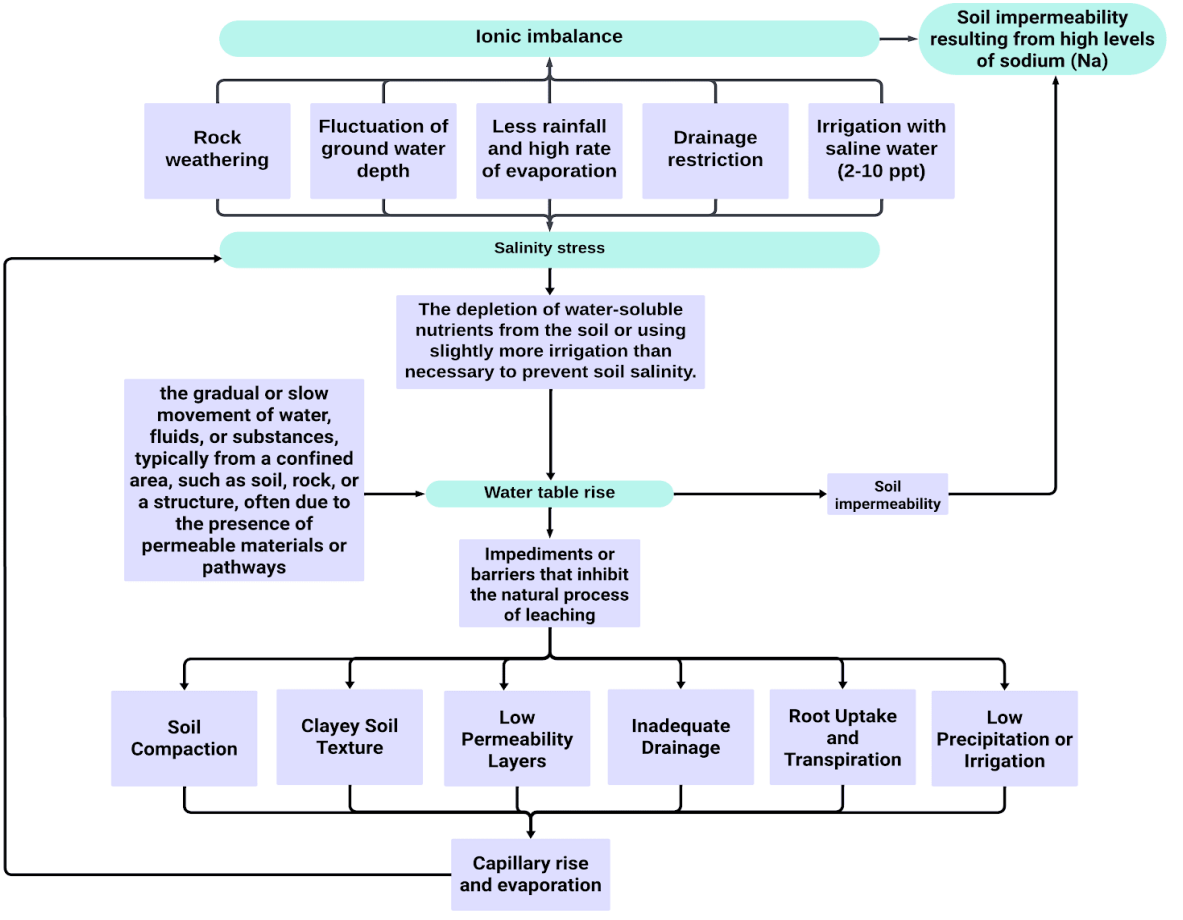

Fig. 3 A theoretical process of soil salinization.[31-35]

saline water or excessive fertilizers, contribute to the initial buildup of salts.[31-35]

A hypothetical cycle of soil salinization initiates with factors like low precipitation or excessive irrigation, leading to the accumulation of salts in the soil (Fig. 3). This accumulation is exacerbated by soil impermeability, which prevents salt leaching. The accumulation of salt creates an ionic imbalance in the soil, further inhibiting plant growth. Additionally, fluctuations in groundwater depth and inadequate drainage contribute to the water cycle by promoting water table rise and capillary rise and evaporation, which concentrate salts at the soil surface.

Soil salinization is a widespread issue affecting agricultural land globally, and it results from a complex cycle driven by various factors that lead to salt accumulation. This cycle starts with natural geological processes, releasing salts into the soil as minerals break down from rocks and parent materials, establishing initial salinity levels in specific regions. Human activities markedly exacerbate this process, notably through the widespread use of saline irrigation water, particularly in arid or semi-arid climates with high evaporation rates, concentrating salts in the soil as water evaporates, gradually elevating their concentration. Inadequate drainage exacerbates this cycle, causing waterlogging and salt accumulation closer to the soil surface. Rising water tables resulting from poor land management or excessive irrigation intensify salt concentrations in soil profiles, thereby amplifying soil salinity. Furthermore, natural processes like surface evaporation and plant transpiration contribute by leaving salts behind as water evaporates, and plants absorb and transpire water containing dissolved salts, increasing their concentration. Human-induced practices, such as excessive fertilizer use, soil additives like lime or gypsum, and disposal of industrial brine or sewage sludge on soil surfaces, perpetuate this cycle, adding to soil salinity. This continuous cycle significantly impacts soil fertility and agricultural productivity by impeding water absorption, causing osmotic stress, reduced nutrient uptake, and stunted growth.[36]

As these salts accumulate, they elevate the soil's salinity levels. Heigh salinity adversely affects soil structure and composition, hindering water infiltration and reducing soil ability to retain essential nutrients. Consequently, plants struggle to absorb water and nutrients, leading to diminished crop yields and plant stress. An imbalance in soil salinity triggers a chain reaction. With reduced plant growth and productivity, there is an increase in unused irrigation water, which further exacerbates the problem of adding more salt to the soil. Additionally, evaporation from the soil surface concentrates the salts, worsening the salinity levels.[37]

This continuous cycle perpetuates soil salinization. Reversing the salinity levels without deliberate intervention becomes increasingly challenging. Implementing sustainable

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agricultural practices, such as proper irrigation management, drainage systems, and soil amendment, can break this cycle by reducing salt input and restoring soil health and productivity.[38] Thus, breaking this hypothetical soil salinization cycle is crucial for maintaining fertile soils and ensuring sustainable agricultural productivity.[39]

Salt-affected soils possess soluble salts or their ions at concentrations exceeding the toxicity threshold, which is the maximum allowable level of salts that do not hinder plant growth.[40,41]

There are two categories of soil salinity: primary and secondary.[42,43] Primary salinity arises from natural salt accumulation driven by environmental factors, such as topography, mineral composition of the earth's surface, rainfall, and groundwater depth, resulting in elevated salt levels in the soil horizon.[44] In contrast, secondary salinity stems from human-related causes like inadequate agricultural practices in unsuitable environmental conditions, excessive fertilizer usage, or improper irrigation water management, including saline water or excessive water application without adequate drainage (Fig. 4).[45-50]

Addressing these different types of soil salinity requires tailored approaches, with primary salinity often requiring more holistic land management strategies and secondary salinity necessitating sustainable agricultural practices to reduce salt accumulation (Fig. 4).

In general, soils affected by salt exhibit diminished productivity, and the impact of salinity is contingent on various factors, including climate, soil characteristics, farming techniques, water management, crop species and cultivars, growth stage, and the composition of salts present.[24] Typically, when plants encounter saline stress, their response unfolds in two discernible phases. Initially, the stress manifests as osmotic stress due to insufficient water, leading to a reduction in growth - a consequence frequently associated with salinity.[51] This reduction in growth is primarily caused by soluble ions such as Cl^-, HCO^{3-}, Ca^{2+}, Na^+, Mg^{2+}, and occasionally NO^{3-} and K^+, which have a detrimental effect on plants by reducing their osmotic potential. As water availability diminishes due to processes like evaporation and transpiration, the water potential also decreases, resulting in a progressively negative osmotic pressure.[50,52] Subsequently, the second phase, known as the ion effect, becomes prominent. This phase initiates and accelerates plant senescence, occasionally leading to toxicity and posing challenges to mineral nutrition.[53]

Salt stress profoundly disrupts photosynthesis in plants. The accumulation of high levels of Na^+ and Cl^- within the leaves triggers water loss from guard cells, precipitating alterations in guard cell and stomata morphology, activity, and/or density. These changes can impede or even obstruct the entry of CO_2, thereby diminishing the efficiency of normal photosynthesis. Furthermore, salt stress induces ion toxicity and oxidative stress, particularly within chloroplasts, which serve as primary sites for the generation of reactive oxygen species (ROS). This dual assault on photosynthetic machinery intensifies the overall negative impact of salt stress on plant growth and productivity.[24,36] Ionic stress encompasses the toxicity resulting from elevated concentrations of Na^+ and Cl^- in the soil solution. This phenomenon can cause mineral

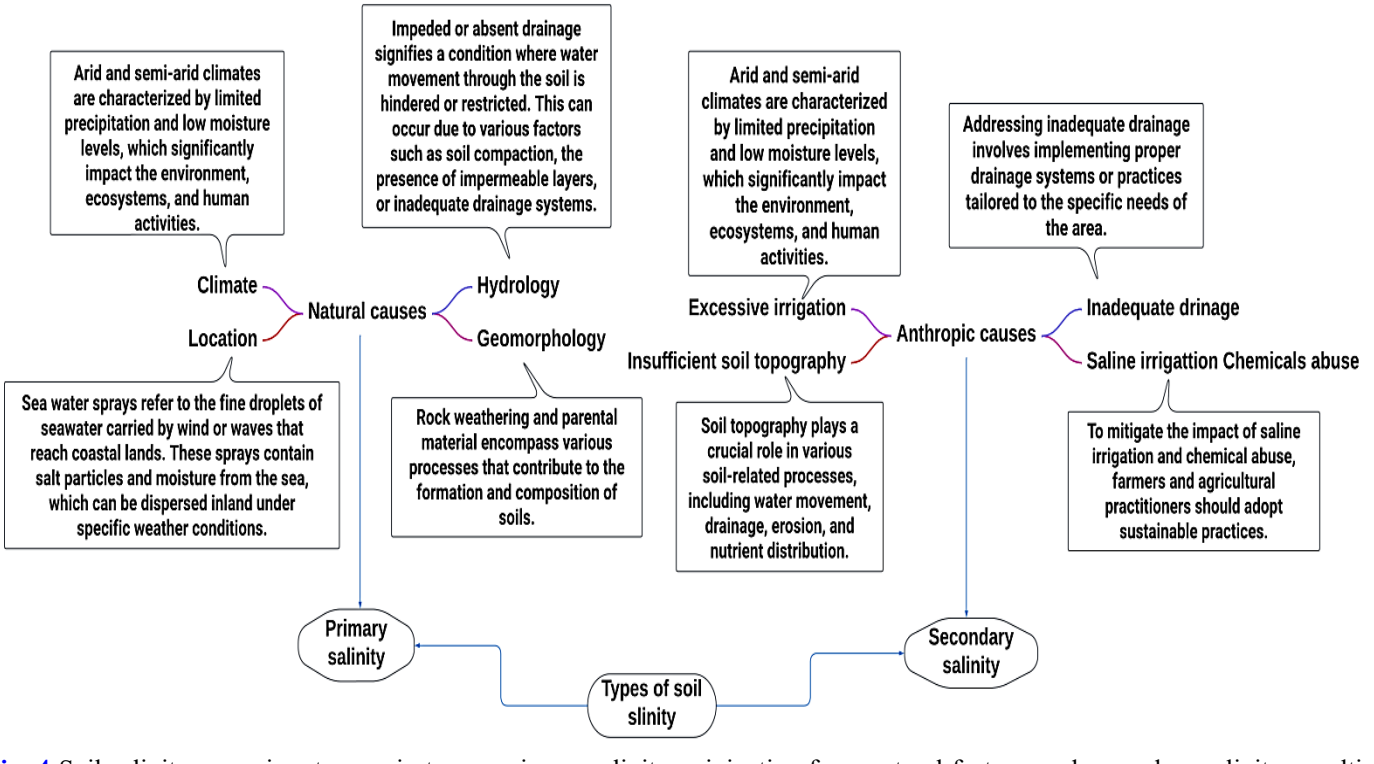

Fig. 4 Soil salinity comprises two main types: primary salinity, originating from natural factors, and secondary salinity, resulting from human-induced or anthropogenic causes.[45-49]

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nutrition issues, including deficiencies in essential minerals such as Ca^{2+}. These deficiencies often arise when the ratio of Na^{+} to Ca^{2+} is elevated in soil water. This imbalance disrupts the normal uptake and utilization of calcium by plants, hindering vital physiological processes. Consequently, plants may exhibit symptoms of calcium deficiency, such as impaired cell wall integrity and reduced structural stability. The interaction between sodium and calcium ions in soil underscores the intricate relationship between ionic stress and mineral nutrition dynamics in plant physiology. This highlights the importance of maintaining a proper soil ion balance to support optimal plant growth and development. These detrimental effects have been documented in numerous agronomic and horticultural crops. Observable indicators of salt injury during plant development emerge gradually. Initial indications of salt stress include drooping, yellowing foliage, and inhibited growth. Subsequently, the harm becomes apparent through chlorosis of previously green tissues, burning of leaf tips, necrosis of leaf blades, and the occurrence of scorching predominantly on the oldest leaves.[54]

In agriculture, the influence of salinity on major cash crops such as corn (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) is intricately tied to their growth stages. These crops exhibit varying degrees of salinity tolerance across different developmental phases. While both corn and soybean exhibit a certain degree of resistance during germination, their tolerance diminishes as they progress through subsequent vegetative growth stages. Research on corn has indicated a decrease in crucial growth parameters like height, dry matter content, leaf area index, and leaf nitrogen content, in response to increasing soil salinity levels, indicating its detrimental impact on plant development.[55] Similarly, the tolerance of soybean to salinity during the growth stages significantly depends on the specific variety to be cultivated. Salinity stress severely impacts soybean plants, resulting in noticeable reductions in plant height, leaf area, photosynthetic efficiency, nutrient uptake, root nodulation, and gas exchange processes.[56] These adverse effects directly affect nitrogen fixation efficiency, particularly in leguminous crops like soybean, underscoring the widespread impact of salinity on crucial physiological processes essential for optimal crop productivity. Therefore, comprehending the stage-specific responses of corn and soybean to salinity stress is crucial in devising targeted mitigation strategies and cultivating more resilient crop varieties to sustain agricultural productivity in saline-affected regions. In summary, salinity can exacerbate adverse effects such as soil aggregate dispersion, transport of organic and inorganic contaminants, erosion, mobilization of soluble salts into groundwater, and release and leaching of heavy metals into the soil solution.[57,58] It can also induce shifts in plant cover, transitioning from mesophytes to halophytes (Fig. 5). These adverse effects of salinity result in environmental and economic costs. Farmer welfare declines due to higher cultivation expenses (loss of soil fertility necessitating fertilizer inputs), reduced revenues (yield decreases, inferior crop quality), and increased maintenance costs (corrosion

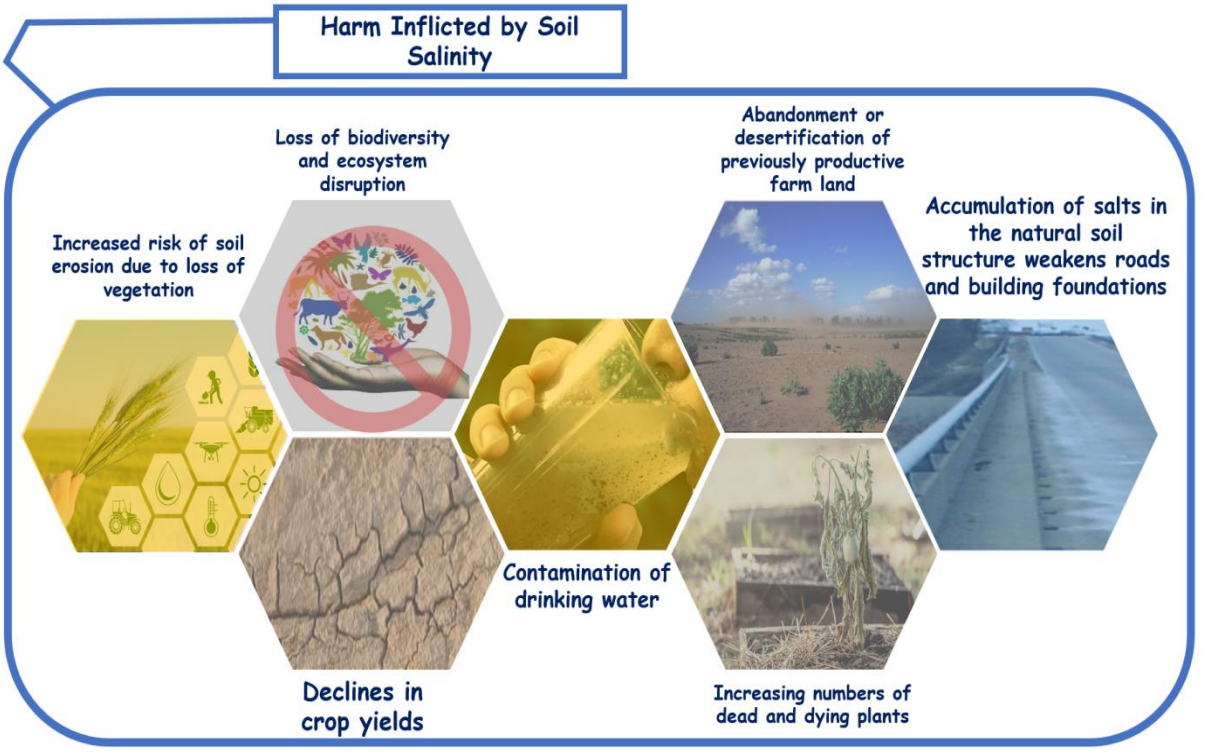

Fig. 5 Adverse impact induced by soil salinity.[51-59]

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shortening infrastructure and machinery lifespan).[60]

Soil salinity can have several adverse effects on soil health, crop productivity, and environmental sustainability. High salt levels can hinder plant growth and nutrient uptake, leading to reduced crop yields and agricultural productivity. Additionally, soil salinity can cause soil degradation, affecting soil structure and fertility, and can also lead to the salinization of water resources, further worsening environmental issues.

A key issue linked to rising soil salinity is the depletion of biodiversity and disturbance of ecosystems. Elevated salt levels change soil characteristics, rendering them unsuitable for numerous plant species. Consequently, the flora and fauna dependent on these plants are displaced or face extinction, resulting in disrupted ecosystems and reduced biodiversity.[61] Deteriorated impact on agriculture due to decreased crop yield stemming from the effects of saline soils. These soils impede the uptake of water and nutrients by plants, resulting in stunted growth and diminished productivity. Consequently, previously fertile farmlands may be abandoned or undergo desertification as salinity renders them unsuitable for cultivation, worsening food insecurity and economic strain. Visible signs of soil salinity manifest through the proliferation of dead or ailing plants. Salinity-induced stress in plant manifests as wilting, leaf scorching, and eventual plant demise, further compounding agricultural losses and environmental degradation.

Furthermore, increasing soil salinity heightens soil erosion risk. The depletion of vegetation caused by salinity undermines the structural integrity of soil, rendering it vulnerable to erosion by wind or water. This erosion intensifies land degradation, compromises soil quality, and depletes fertile topsoil. Potable water contamination is a pressing issue associated with elevated soil salinity. Salts infiltrate groundwater sources, compromise the quality of drinking water, posing risks to human health and necessitating costly purification procedures. Moreover, the accumulation of salts within the natural soil matrix weakens the foundations of critical infrastructure such as roads and buildings. This structural instability poses hazards to public safety and imposes financial burdens on maintenance and repair efforts.[62] Moreover, increasing saline water table has a detrimental effect on soil biological activity. Elevated groundwater salinity impede the growth and function of beneficial soil organisms, affecting nutrient cycling and overall soil health. This reduction in biological activity intensifies soil degradation and diminishes its ability to sustain robust vegetation.[63]

The repercussions of increasing soil salinity are widespread and profound, impacting ecosystems, agriculture, infrastructure, and human welfare. Addressing these challenges requires holistic approaches centered on sustainable land management practices, prudent water utilization, soil restoration efforts, and the adoption of resilient crop varieties. Effective mitigation of soil salinity is imperative not only for safeguarding ecosystems and agricultural output but also for fostering the sustainability of societies and the environment despite this pervasive environmental concern.[64]

3. Soil salinity assessment

Soil salinity, a widespread issue affecting various regions

Fig. 6 Visible signs of soil salinity.

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worldwide, presents itself through several discernible indicators, that offer crucial insights into its profound impact on ecosystems and agricultural productivity (Fig. 6).[1]

One of the most conspicuous signs of soil salinity is the formation of white salt deposits, which form a crust-like layer on the soil surface. This crystalline layer serves as a clear indication of salt accumulation resulting from moisture evaporation, leaving behind salt residue and altering soil physical properties, often rendering it powdery. Additionally, salt stains are visible on the dry soil surface, even in the absence of crust formation, and serve as visual indicators of salt concentrations within the soil.[37] These visible manifestations of soil salinity indicate a significant impact on agriculture, particularly on seed germination and crop growth. Elevated salinity levels impede seed germination, leading to reduced or failed germination rates. Consequently, crop growth becomes irregular and uneven, as the inhospitable conditions hinder optimal plant development, resulting in patchy crop establishment and diminished vigor in plant growth.[65,66]

Foliage bears the brunt of soil salinity, and exhibits signs of distress, such as leaf scorching or burn, indicating damage caused by excessive salt exposure. Leaves also undergo noticeable color and shape changes, with discoloration and deformities being common of salinity stress.

In regions affected by soil salinity, the prominence of naturally occurring salt-tolerant plants, termed halophytes, becomes more pronounced. These indicator species thrive in environments with high salt levels, serving as signals of elevated soil salinity levels. Trees, particularly those sensitive to salinity, exhibit signs of deterioration or mortality in salt-affected regions. Soil salinity often disrupts the equilibrium of essential nutrients, resulting in the decline and eventual demise of trees unable to withstand these adverse conditions. Interestingly, rather than experiencing rejuvenation after rainfall, salt-affected areas deteriorate further. The infiltration of water into saline soil intensifies the issue as it dissolves salts, forming toxic solutions for plants. Additionally, waterlogging occurs in certain areas due to the soil's diminished capacity to absorb water, creating saturated conditions detrimental to plant growth.[57,62,67]

4. Contemporary methods for rehabilitating saline soils

Contemporary techniques for restoring saline soils involve innovative approaches that mitigate the adverse effects of salinity while revitalizing soil health.[67] These methods encompass various strategies, including phytoremediation, precision irrigation, and soil amendment. Phytoremediation involves the use of salt-tolerant plants, such as halophytes, to extract salt from soil and alleviate soil salinity. Precision irrigation methods, like drip or sprinkler systems, optimize water usage by directly delivering precise amounts of water to plant roots, thereby reducing waterlogging and salt accumulation. Additionally, soil amendments like gypsum or organic matter can aid in improving soil structure and enhancing its ability to buffer against salinity.[68] These contemporary approaches prioritize sustainable practices that restore soil fertility, promote crop productivity, and mitigate the environmental impact of saline soils. These advanced techniques offer promising avenues for effectively addressing the challenges of soil salinity in modern agricultural landscapes.[69]

Ethylenediamine-N,N'-disuccinic acid (EDDS), chitosan (CH), fucoxanthin (FX) and other organic amendments have been extensively researched for their potential application as soil amendments in agriculture owing to their various advantageous characteristics.[70-74] For example, this study explores the potential of CH as an organic amendment to mitigate the impact of polystyrene microplastics (PS) on soil properties and plant growth. Although PS has a minimal influence on soil pH, CH significantly lowers pH levels. CH thus shows promise in mitigating nutrient depletion and enhancing organic matter in soil. In terms of crop growth, PS inhibits growth, whereas CH stimulates growth, affecting various growth metrics. The complex interplay between CH and PS highlights the need for further research to understand their interaction and long-term effects on soil and crop health.[70] Moreover, another study highlighted the potential of fucoxanthin (FX) as a soil amendment to promote plant growth and mitigate the effects of environmental stressors on agriculture. This study investigated the effects of Polystyrene microplastics (PS) and FX on soil and maize growth. PS decreased soil pH and negatively affected maize growth, while FX increased available nutrients, reduced electrical conductivity, and improved maize growth, suggesting FX's potential as a soil amendment to counteract the negative effects of PS and enhance plant growth.[71-73]

4.1 Salinity reduction by leaching

Leaching to obtain favorable conditions for seed germination or plant establishment is an essential strategy for the reclamation of salt-affected land, almost notably for arid and semi-arid environments. In natural ecosystems, the concentration of soluble salts in surface soils increases with evaporation and increased arid conditions and may also lead to salt precipitation.[74, 75] Salt gathers on the soil surface without drainage, hindering seed germination and plant growth. Salt leaching is intended to diminish solutes from the

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upper soil layers. The leaching of soluble salts from soil may occur naturally through rainfall in ecosystems with deep drainage potential. In such cases, the quantity and pattern of rainfall are crucial for salt leaching, as prolonged dry spells and changes in solute flow direction can bring salt back to the soil surface.[76,77]

Soils featuring layers or horizons with low hydraulic conductivity pose constraints on downward water movement, impeding effective leaching processes. Saline-sodic soils commonly exhibit inadequate physical conditions and low hydraulic conductivity, infiltration rates, and drainage capabilities. To ameliorate these challenges, tailored approaches are essential to enhance soil physical properties, facilitate salt leaching, and foster conditions conducive to seed germination.[76]

Soil pores facilitate the movement of water and air within soil, with macropores playing a crucial role in water and solute transport. Although macropores contribute only a small fraction of total soil porosity, they exert a significant influence on overall water flow. Macropores enhance downward water movement, promoting greater soil infiltration.[76] This increased water volume facilitates the transport of dissolved solutes deeper into the soil profile, enhancing leaching processes. In saline-sodic soils, which are characterized by poor aggregation and inadequate pore networks, particularly those lacking macropores or interconnectivity, suitable conditions for salt leaching cannot be established, particularly in regions with limited and irregular rainfall such as semi-arid environments. Implementing reclamation strategies to improve soil pore structure can aid in leaching salts, thereby facilitating plant germination and subsequent revegetation efforts.[78]

4.2 Addition of organic amendments as ameliorants

Organic matter plays a pivotal role in soil structure formation and the development of aggregates and pore systems. The significance of soil chemistry stems from its high specific surface area and colloidal characteristics.[79] As a binding agent between and within aggregates, organic matter enhances the stability of soil aggregates and improves their water-holding capacity.[78] Moreover, it facilitates infiltration and water passage, enhancing the overall soil pore system.[80] Several studies have highlighted the potential of organic amendments to improve salt leaching in soil. Incorporating organic materials into saline soils, researchers observed reductions in salt content and improved soil chemical properties. Organic amendments offer promise in addressing issues such as high sodium ion levels, exchangeable sodium percentages, and electrical conductivity in saline soils.[81]

However, not all organic materials are equally effective in soil reclamation efforts. While some organic amendments show promise in improving soil conditions, others may inadvertently contribute to soil salinity and sodicity. Manure, such as cattle and poultry manure, and composts have been implicated as sources of salt in the soil.[82] This underscores the importance of carefully selecting appropriate organic amendments based on their chemical composition and potential impacts on soil salinity levels. In addition to addressing soil salinity, organic amendments can have broader implications for soil health and fertility. By promoting microbial activity and nutrient cycling, organic matter enhances soil biological processes.[83] Microorganisms play a crucial role in decomposing organic matter, releasing essential nutrients that are then available for plant uptake.[84]

The benefits of organic amendments extend beyond soil chemistry, extending to soil physical properties as well. Organic matter improves soil structure by promoting aggregation and reducing compaction. Enhanced soil structure enhances root penetration and proliferation, facilitating better water and nutrient uptake by plants. Moreover, organic matter can mitigate soil erosion by improving soil stability and reducing surface runoff. In agricultural systems, the use of organic amendments is widely recognized as a sustainable practice for soil management. Organic farming practices prioritize the use of natural inputs such as compost and manure to enhance soil fertility and productivity.[85]

4.3 Halophytes for phytoremediation

Rehabilitating saline-sodic soils can be accomplished by revegetation using a plant-centered approach to enhance soil quality. This strategy relies on the intricate interactions among plants, soil components, and hydrology.[86] Phytoremediation, which utilizes plants for soil rehabilitation, can be effectively managed, with the added advantage of potential fodder utilization in certain instances. Interestingly, in specific contexts, phytoremediation of saline-sodic terrain has produced results comparable to traditional engineering methods.[87] A recent study found that while gypsum application reduced sodicity, its efficacy was confined primarily to the surface layer.[88] In contrast, phytoremediation reduced sodicity in the entire plant root zone, demonstrating greater efficiency. It is noteworthy that initially, gypsum application may raise soil salinity levels. However, the subsequent enhancement of soil hydraulic conductivity facilitated by gypsum allows for salt leaching, ultimately leading to decreased salinity levels.[89]

Saline-sodic soils can undergo remediation through revegetation utilizing halophytes.[86] Certain halophyte species,

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such as *Salicornia europaea* and *Salicornia bigelowii*, require added NaCl for optimal growth, while others thrive under moderate salinity conditions.[90] Numerous studies have documented the successful reclamation of saline-sodic soils using halophytes.[91] Species like Suaeda maritima, Suaeda portulacastrum, Suaeda salsa, Suaeda fruticose, Atriplex nummularia, and Atriplex prostrata have shown remarkable tolerance to high levels of Na+ and can accumulate significant Na+ concentrations in their tissues, rendering them effective for the revegetation and reclamation of saline lands.[92] Moreover, halophyte roots contribute to soil structure improvement by creating pores, thereby enhancing water and airflow.[93]

4.4 Removal of salt from agricultural land affected by salinity via scraping

Saline terrain can undergo physical reclamation through salt scraping, which involves removing the salt crust to facilitate the re-establishment of plants.[94] Typically, this process is followed by leaching to eliminate salts, including sodium ions, from the root zone. In moderately saline-sodic conditions, calcium-ion amendments may be necessary to displace exchangeable sodium ions.[95] However, the efficacy of salt scraping as a saline soil remediation method depends on several factors, such as the dynamics of salt precipitation. High evaporation rates can cause salts to migrate upward toward the soil surface, while significant rainfall events can leach salts to deeper soil profile depths, where they may not resurface.[96] Therefore, the suitability of this strategy may be limited to specific land and climatic conditions without addressing the underlying causes of salt crust formation.

5. Effect of biochar on restoring saline soils

Microorganisms constitute integral and dynamic components of soil ecosystems and participate in nearly all biological and biochemical reactions within the soil matrix. They play crucial roles in processes such as the decomposition of soil organic matter, nutrient cycling and transformation, and the development of soil structure.[97] However, excessive base cations and elevated pH levels in saline soils can create a hostile environment for microorganisms, inducing osmotic stress and nutrient deprivation, which can impair microorganism activity and abundance. Consequently, the total microbial population in saline soils tends to be lower than that in non-saline soils within the same ecological region, with composite saline soils exhibiting even fewer microorganisms than single saline soils.[98]

Biochar, a carbon-rich material derived from biomass, offers several benefits to soil microorganisms (Fig. 7). It serves as a source of carbon and mineral nutrients, provides a conducive habitat due to its large specific surface area and porous structure, and enhances water and nutrient retention in

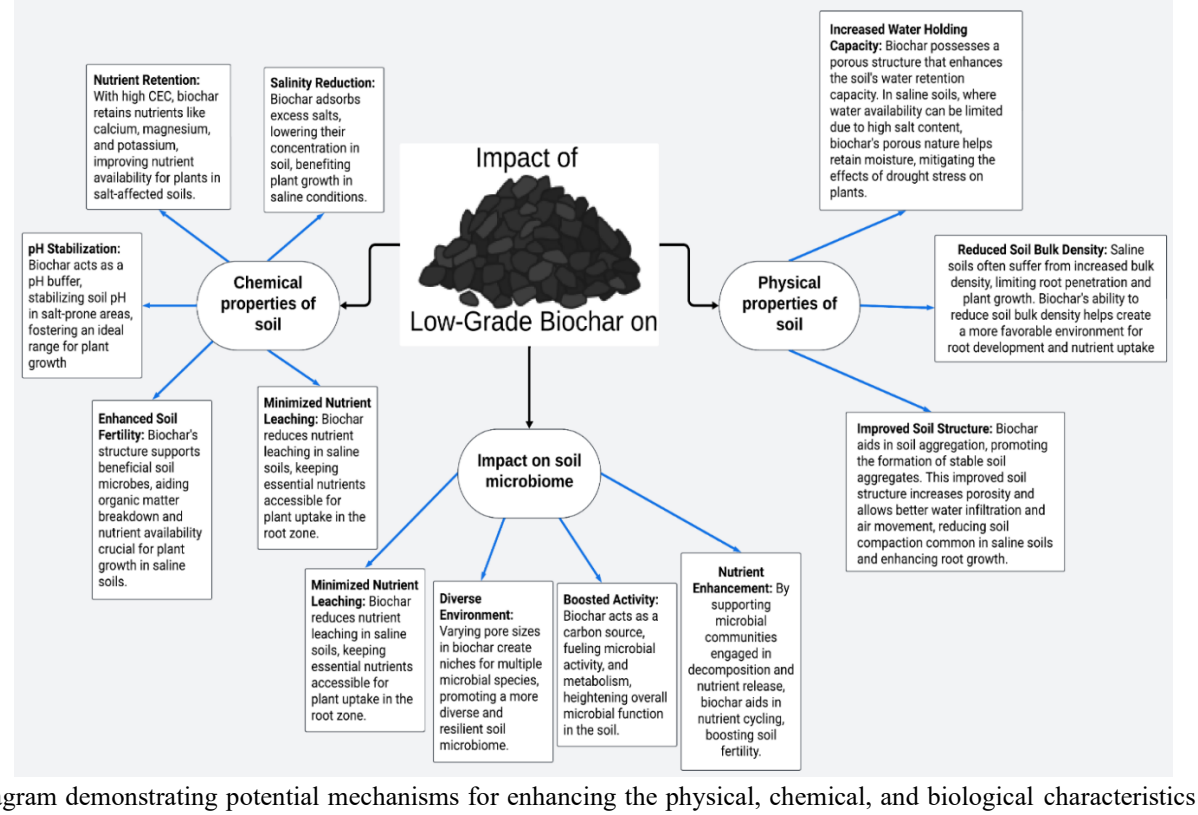

Fig. 7 Diagram demonstrating potential mechanisms for enhancing the physical, chemical, and biological characteristics of saline soils by incorporating biochar.

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the soil.[99,100] Moreover, biochar exhibits strong adsorption properties for salt-based ions, mitigating microbial salt stress and promoting microbial respiration rates and carbon content in biomass.[101] Additionally, biochar has been shown to reduce methane emissions from saline soils by modulating the abundance of methane-producing and methane-oxidizing microbial genes.[102] Furthermore, the addition of biochar to saline soils has been associated with an increase in the relative abundance of soil nitrogen-fixing bacterial taxa and ammonia-oxidizing microorganisms, thereby enhancing nitrogen cycling and nitrification processes.[103]

Some studies have demonstrated that biochar amendments can improve soil microbial community structure and function by providing direct shelter, improving soil physicochemical conditions, and supplying essential nutrients, such as carbon, nitrogen, and phosphorus.[104,105] However, it is important to acknowledge that certain biochar materials may contain hazardous substances such as polycyclic aromatic hydrocarbons and heavy metals, which could adversely affect microbial communities in salt-affected soils.[106] Despite the growing body of evidence supporting the positive effects of biochar on saline soils, there remains a lack of consensus regarding the response of soil microorganisms to biochar amendments in saline environments. Thus, further research is warranted to investigate the impact of biochar on key functional microbial populations in saline-alkaline soils, including those involved in nitrogen fixation, nitrification, phosphorus solubilization, and plant-microbe symbiosis.[107,108] The research on biochar as a beneficial amendment for saline soil has seen significant growth, with advancements made over the years.[99] Biochar has a positive impact on enhancing the structure of saline soil, expediting salt leaching, bolstering soil water retention and fertilizer retention capacities, augmenting soil microbial activity and abundance, and fostering crop growth.[109] Despite the global distribution of saline soils across diverse climates and varying degrees of salinization, the effectiveness of biochar in improving soil properties can be influenced by factors such as the type of biochar, application quantity, and vegetation type.[110,111] However, the outcomes of biochar application often fall short of expectations and may even exacerbate the issue. Consequently, research on the effects and mechanisms of biochar on improving saline soil remains inadequate, prompting the need for further investigation.

Moving forward, research efforts should prioritize understanding the role of biochar properties in soil remediation and standardizing the selection of raw materials, preparation processes, and biochar modifications.[112] Additionally, integrating biochar with other soil amendments, such as organic fertilizers, humic acids, or wood vinegar, and developing practical application techniques are crucial for maximizing ecological and economic benefits in agricultural settings.[113] Furthermore, future studies should adopt a holistic approach by combining short-term laboratory investigations with long-term field studies to account for biochar aging in soil and bridge the gap between laboratory findings and real-world agricultural practices.[114] Moreover, focusing on the rhizosphere and employing cutting-edge genomics technologies can provide deeper insights into biochar-soil interactions, microbial dynamics, and nutrient cycling processes in saline soil environments, ultimately aiding in optimizing soil improvement strategies for enhanced agricultural productivity.

When incorporating biochar amendments into saline soils, farmers and land managers take into account various practical suggestions. Primarily, the careful selection of biochar specifically tailored for saline soils or validated to be efficient under such circumstances is of utmost importance. The determination of the application rate should be conducted meticulously, considering factors such as soil composition, crop type, and salinity level, starting with a small amount and increasing as necessary. To ensure proper assimilation, biochar should be meticulously blended with soil prior to planting or during soil preparation. Regular monitoring of soil salinity levels, plant development, and soil conditions is crucial for evaluating the efficacy of biochar amendments. Furthermore, farmers should contemplate crop choices, water management techniques, and strategic planning for long-term benefits of biochar usage while mitigating environmental repercussions. Seeking guidance from agricultural specialists or researchers can offer customized recommendations for the successful execution of these strategies.

6. Impact of bacterial species on solubilizing LRC

Extensive research has focused on the solubilization of LRC by different bacterial species due to its potential significance in bioremediation, bioenergy, and environmental uses. Several of these bacterial species have shown proficiency in either solubilizing LRC or aiding its decomposition.[115] For instance, *Pseudomonas putida* is a versatile bacterium known for its metabolic capabilities. Studies have shown its potential in solubilizing LRC through the secretion of enzymes that facilitate the breakdown of complex organic compounds within coal.[116,117] Similarly, *Acinetobacter baumannii* has been investigated for its enzymatic activity that could aid in coal degradation.[118] Moreover, *Bacillus* species, including *Bacillus mycoides* and *Bacillus subtilis*, have been identified to produce ligninolytic enzymes and oxidoreductases.[119]

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These enzymes are vital for facilitating the decomposition of lignin-like substances found in coal, thereby facilitating its solubilization. Similarly, *Microbacterium sp*. and *Streptomyces setoni* have been subjects of interest due to their potential enzymatic activities involved in coal degradation. These bacteria may secrete enzymes capable of breaking down complex coal structures into simpler forms, thereby enhancing solubilization.

Citrobacter freundii is recognized for its metabolic diversity and may contribute to coal solubilization through various metabolic pathways. *Staphylococcus aureus* and *Staphylococcus xylosus,* although not extensively studied for coal solubilization, possess metabolic potential that warrants investigation in coal degradation processes. In addition, *Pseudomonas rathonis* and *Pseudomonas fluorescens* exhibit enzymatic activities relevant to lignin degradation and might contribute to coal breakdown processes. *Pseudomonas oleovorans* and *Rhodococcus ruber* are promising candidates to use coal-derived products as carbon sources for growth, indicating their potential roles in coal solubilization. The solubilization of LRC by these bacterial species primarily involves the secretion of enzymes such as ligninases, peroxidases, oxidoreductases and other hydrolytic enzymes. These enzymes help to break down the complex organic structures in coal, making it more soluble and accessible.[116-123] The process of coal solubilization by these bacteria can have significant environmental implications. It could be harnessed for bioremediation to clean up coal-contaminated sites or aid in extracting valuable compounds from coal for energy production. Moreover, understanding the mechanisms and specific enzymes involved in coal solubilization by these bacteria can pave the way for developing bioaugmentation strategies or engineered microbial systems for enhanced coal bioprocessing. However, despite the promising potential of these bacterial species for coal solubilization, several challenges remain. Optimizing conditions for microbial growth and activity on a large scale, ensuring efficient coal degradation, and addressing issues related to releasing potentially harmful byproducts during the process are among the key challenges that need further exploration.[116,120]

Overall, the diverse array of bacterial species mentioned exhibits varying degrees of potential for solubilizing LRC. Harnessing their enzymatic activities and metabolic pathways could lead to innovative strategies for coal bioprocessing, offering environmentally sustainable solutions to various industries reliant on coal-derived products. Continued research into the mechanisms of these bacterial species and optimization are crucial for unlocking their full potential in coal solubilization and related applications.

Bacillus mycoides CSB25, *Microbacterium* sp. CSB3, *Acinetobacter* sp. CSB13, and Enterobacter aerogenes CSB10 have been isolated from coal residues, coal sediments, and rhizospheres. They were selected based on their ability to grow in a medium containing powdered coal, indicating their potential to interact with and degrade coal components. These bacteria have been studied for their ability to solubilize LRC in a solid matrix and biotransform it into humic substances (HS) in liquid medium. The study focused on lignite coal from the El Cerrejón opencast mine in Colombia, characterized by its composition: humidity - 28.44%, ash (A) - 11.12%, volatile matter (V) - 47.79%, fixed carbon (FC) - 41.09%, and calorific value (Q) - 4781 Kcal Kg^{-1}. The elemental composition of coal includes carbon (C) - 46.04%, hydrogen (H) - 3.26%, oxygen (O) - 42.95%, nitrogen (N) - 1.38%, and sulfur (S) - 0.13%. The bacteria were found to facilitate LRC biotransformation at rates ranging from 25% to 37% and HS production ranging from 127 to 3100 mg L^{-1}. The E4/E6 ratio values were 5.2 for bio-HA and 4.8 for chem-HA, indicating differences in the composition of the produced HS. Bio-HA showed higher contents of nitrogen (N), carbon (C) and hydrogen (H), and a lower content of oxygen (O) than chemically produced HA. The infrared spectra of bio-HA exhibited similar qualitative characteristics to those of chemically produced HA. The supramolecular structures of both HA types had moderately high molecular weights, primarily due to molecules with high aromatic condensation. These findings suggest that bacterial isolates can be used to exploit lignite coal to produce humic substances, with implications for environmental and industrial applications.[124] *Bacillus mycoides* CSB25, *Microbacterium* sp. CSB3, *Acinetobacter* sp. CSB13, and Enterobacter aerogenes CSB10 employ various mechanisms to break down LRC and enhance solubilization. These bacteria produce a range of enzymes, including lignin-degrading enzymes, cellulases, and hemicelluloses, which target the complex organic molecules in lignite coal. These enzymes work synergistically to degrade the lignocellulosic structure of coal, breaking it down into simpler, more soluble compounds. Additionally, these bacteria produce organic acids and other metabolites as byproducts of their metabolism. These organic acids help solubilize both the organic and inorganic components of lignite coal by lowering the pH of the surrounding medium. The acidic environment created by these metabolites enhances the solubility of coal components, facilitating their breakdown and subsequent utilization by bacteria. Furthermore, these bacteria can form biofilms on the surface of coal particles. This biofilm formation increases the surface area available for solubilization and enhances the contact between bacteria and

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coal particles, leading to more efficient degradation and solubilization processes. These combined mechanisms enable these bacteria to efficiently break down lignite coal and enhance the solubilization of its components, making them promising candidates for coal biotransformation and humic substance production.[125]

Various bacteria species were identified for their ability to solubilize LRC (Table 1). *Pseudomonas putida* was found to significantly improve the biodegradability of lignites and sub-bituminous coals, with approximately 90% solubilization of lignites and around 40% of sub-bituminous coals achieved after treatment with nitric acid before oxidation. *Bacillus mycoides* was studied for its impact on saline-sodic soils when applying LRC, which facilitated microbial activity and biotransformation processes, aiding in soil restoration. Additionally, *Bacillus mycoides* and other bacteria were found to produce HS through the solubilization of LRC, suggesting potential applications for enhancing soil health. *Citrobacter freundii* was examined for its ability to solubilize Spanish coal, leading to the generation of an extracellular polymer that potentially aids in the adhesion of microorganisms to coal surfaces. These findings highlight the diverse capabilities of bacteria for solubilizing LRC and their potential applications in environmental and soil remediation processes.

Expanding the discussion of the environmental implications of coal solubilization by bacteria reveals both potential benefits and challenges. One significant benefit is the potential for the bioremediation of coal-contaminated sites. Bacteria capable of solubilizing coal can break down the complex hydrocarbons in coal, thereby reducing its environmental impact. This process can help in clean up coal waste sites, improve soil quality, and reduce groundwater contamination. However, there are also challenges and risks associated with coal solubilization. One major concern is the release of potentially harmful substances during coal breakdown, such as heavy metals and organic pollutants, which could further contaminate the environment if not properly managed. Additionally, the use of bacteria for coal solubilization may require the addition of nutrients or other amendments to support bacterial growth, which could have unintended environmental consequences if not controlled. Furthermore, the long-term effects of bacterial coal solubilization on soil health and ecosystem functioning are not yet fully understood. It is essential to conduct thorough environmental assessments and monitoring when implementing this technology to ensure that any potential risks are minimized and that the benefits outweigh the environmental costs.

Table 1. Known bacteria species to solubilize low-rank coal.

Bacteria species	Purpose(s)	Result(s)	References
Pseudomonas putida	To observe and analyze the impact of microbiological treatment involving *P. putida* bacteria on the chemical composition or structure of lignites and subbituminous coal obtained from Polish mines.	Treatment with nitric acid before oxidation significantly improved biodegradability, leading to approximately 90% solubilization of lignites and around 40% of sub-bituminous coals.	[116]
Bacillus mycoides *Acinetobacter baumannii* *Microbacterium sp.*	To assess the impact of applying LRC, specifically lignite type, in saline-sodic soils. Additionally, the research aimed to investigate the influence of bacterial inoculation designed to release HOM derived from this particular coal type.	Applying LRC could facilitate microbial activity, thereby expediting the biotransformation processes of LRC. This, in turn, may aid in the restoration or rehabilitation of these disrupted soils.	[118]
Bacillus mycoides	The assessment analyzed the production of HS achieved via the bacterial solubilization of LRC.	The findings indicate that these bacteria have the potential to utilize the LRC generated from coal mining operations to produce HS. Consequently, this process can be utilized to enhance the levels of HOM in soils as a means of improvement.	[119]
Citrobacter freundii *Pseudomonas rathonis* *Pseudomonas fluorescens* *Streptomyces setoni*	To gain understanding of the processes of biosolubilization, the ability of cell-free culture filtrates from fungi was examined to determine their effectiveness in solubilizing various types of Spanish	When bacteria were cultivated in the presence of coal, they generated an extracellular polymer that could potentially adhere microorganisms to the coal surface. Additionally, a	[120,121]

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	coal.	significant number of structures resembling lipid bodies were noticed within the bacterial cells that were cultured alongside coal.	
Pseudomonas oleovorans	To conduct a screening process aimed at identifying specific bacteria capable of utilizing chemically diverse LRC to liquefy products as complex carbon sources for growth, resulting in the discovery of two such bacteria.	*Pseudomonas oleovorans* and *Rhodococcus ruber* were observed to amass polyhydroxyalkanoic acids (PHA) at approximately 2%±8% of the cell dry weight when cultivated solely on these liquefaction products without any additional carbon sources. It was observed that LRC served as a more effective substrate for *P. oleovorans* than chemically produced fulvic acids.	[122]
Rhodococcus ruber			
Bacillus subtilis *Staphylococcus aureus*	The analysis aimed to identify and characterize the specific microorganisms capable of enduring and surviving within the LRC over an extended duration.	The existence of microorganisms within native lignite was confirmed through various methods, including fluorescence microscopy, scanning electron microscopy, and electron microprobe analysis. These results provide conclusive evidence that microorganisms can survive in LRC for extended periods.	[123,124]
Staphylococcus xylosus			

Future research directions in the domain of bacterial-facilitated LRC solubilization might focus on the enhancement of bacterial strains to enhance solubilization efficacy, the innovation of new enzymatic pathways to enhance coal decomposition, and the incorporation of bioremediation methodologies with alternative environmental remediation approaches to tackle intricate environmental dilemmas. Through the exploration of these pathways, scholars can further promote the utilization of bacterial solubilization in environmental rehabilitation, sustainable agriculture, and other domains, thus laying the groundwork for inventive and environmentally sustainable solutions to urgent environmental challenges.

The use of bacteria and coals to restore soil salinity presents several advantages, including their potential to enhance soil health and crop vitality and their natural and sustainable nature (Table 2). However, there are weaknesses, such as a limited understanding of their long-term effects and the need for further research to optimize their application. Opportunities include the development of innovative soil restoration techniques, while threats include environmental risks and resistance to traditional farming practices.

7. Recent advances in bacterial LRC solubilization

Recent progress in the solubilization of LRC by bacteria represents a promising area of study in biotechnology, offering potential benefits across multiple industries. This process involves converting LRC into a soluble form with the help of microorganisms, particularly bacteria. In recent years, significant advancements have been made in understanding the mechanisms behind bacterial solubilization and its practical applications. One notable breakthrough is the identification of specific bacterial strains and their enzymatic abilities, which enable them to effectively break down complex organic compounds present in LRC.[47] Enzymes such as ligninases, peroxidases, and oxygenases produced by these bacteria have been pinpointed for their role in degrading the intricate molecular structures of coal. Through their action, these enzymes facilitate the release of soluble organic matter, humified organic compounds, and other bioactive substances from LRC, making it more accessible for microbial degradation and utilization. These discoveries in enzyme identification and characterization have spurred further research into harnessing bacterial solubilization for various practical applications.[52]

The utilization of bacterial-driven LRC solubilization offers diverse and promising prospects across various fields. One notable application of this approach is in environmental restoration, particularly in bioremediation efforts aimed at reclaiming polluted sites. Bacterial solubilization of LRC can assist in breaking down organic pollutants and hazardous substances found in contaminated soils or environments,

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Table 2. SWOT analysis of the use of bacteria and coals to restore soil salinity.

Strengths	Weaknesses
1. Bacteria can break down complex organic molecules in coal, releasing nutrients that promote soil fertility. 2. Bacteria can enhance the solubilization of coal components, leading to the production of humic substances that improve soil structure and water retention. 3. The use of bacteria and coal can be a cost-effective and sustainable approach to soil restoration, especially in areas with high coal availability.	1. The process of using bacteria and coal for soil restoration may take time and requires long-term monitoring and management. 2. Limited research has been conducted on specific bacterial strains and coal types suitable for different soil types and salinity levels. 3. The effectiveness of this approach may vary depending on environmental conditions and the presence of other contaminants in the soil.
Opportunities:	Threats:
1. Continued research and development can lead to the identification of more efficient bacteria strains and coal types for soil restoration. 2. Collaborations with local communities and stakeholders can help promote the adoption of this approach in areas affected by soil salinity. 3. The use of bacteria and coal for soil restoration can contribute to sustainable land management practices and environmental conservation.	1. There may be resistance or skepticism from traditional agricultural practices and industries in adopting new approaches like using bacteria and coal for soil restoration. 2. Environmental regulations and policies may restrict or limit the use of coal-based products in soil restoration due to concerns about environmental impact. 3. The long-term effects of using bacteria and coal for soil restoration on soil health and ecosystem balance are not yet fully understood, which poses potential risks to ecosystem stability.

providing a sustainable and environmentally friendly method for soil and water cleanup. Furthermore, the solubilization process yields HOM from coal, which can notably enhance soil quality and fertility.[11] HOM derived from solubilized coal acts as an organic supplement, improving soil structure, moisture retention, and nutrient availability. This approach presents an innovative approach for rehabilitating depleted soils, particularly in arid and degraded regions, promoting sustainable agriculture and ecosystem rejuvenation.[15]

Additionally, recent research focused on LRC solubilization by different bacterial species underscores the potential for extensive biotechnological applications and sustainable resource utilization. These studies delved into the diverse capabilities of bacteria in breaking down LRC, emphasizing the specific roles of bacterial strains in the solubilization process. By exploring the enzymatic capacities of various bacterial species, researchers have revealed broad potentials for bacterial solubilization across various fields. Moreover, these studies sought to summarize and assess collective findings, thereby revealing promising applications of bacterial solubilization beyond environmental remediation. The insights derived from these research efforts can transform industries by providing eco-friendly solutions and driving progress in sustainable energy, environmental protection, and biotechnological advancement.[57]

In summary, recent advancements in LRC solubilization by bacteria represent a significant shift in biotechnological strategies with far-reaching implications. Understanding the enzymatic capabilities of specific bacterial species and their involvement in solubilization is crucial for harnessing this process across various domains. These applications range from environmental cleanup, soil revitalization, and sustainable farming to renewable energy sources and industrial progress. These breakthroughs mark a new chapter in biotechnology, paving the way for environmentally friendly solutions, resource reclamation, and sustainable growth across multiple sectors. Further exploration and application of bacterial solubilization in LRC offers potential for addressing environmental issues and fostering a more sustainable future.

8. Challenges and limitations associated with the use of solubilized LRC as an organic amendment

One of the paramount challenges anticipated in the forthcoming years is the transition of the agriculture sector from a conventional model reliant on synthetic fertilizers towards a more sustainable approach known as regenerative agriculture. This transition involves the incorporation of manure and organic residues alongside the reduction of fertilizers. It is imperative to prioritize the reuse of residues as soil enhancements, whether directly or after certain transformations, as the primary option for managing organic waste from agricultural and agro-industrial activities. In accordance with the principles of the waste hierarchy, the burning or disposal of these residues should only be considered as a last resort. Consequently, recycling these organic residues back into the soil emerges as a logical choice

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that not only mitigates soil degradation and unsustainability and presents opportunities to convert residues into valuable resources.[88,90-112]

Nevertheless, accomplishing this overarching objective requires extensive transformations, encompassing not only advancements in soil, waste, and crop management practices but also a socioeconomic revolution. Over the past few decades, there has been a noticeable surge in the use of synthetic fertilizers coupled with a stagnant application of manure as a nitrogen source, resulting in plateauing crop yields and declining soil health across various regions globally. Future research should focus on closing nitrogen, phosphorus, potassium, and carbon loops, thereby ensuring balanced fertilization to produce nutrient-rich foods for both animal and human consumption. Economic factors also come into play, as the energy-intensive nature of synthetic fertilizers underscores the dire need for a complete overhaul. Additionally, the scarcity of raw materials for fertilizers due to political factors necessitates exploring alternative organic sources. Future research directions should also emphasize safe food production practices to mitigate the presence of emerging contaminants like pesticides or microplastics.[115,117-120]

Another potential issue lies in the insufficient land availability for many farms to effectively recycle the organic waste they generate or to implement the required technology for biological or thermal conversion. Hence, comprehensive waste management systems must be established on a larger scale, encompassing collection, treatment, and/or distribution from surplus-producing regions to areas with deficiencies. Establishing cooperatives among farmers for waste processing could offer a viable solution for large-scale waste management. Furthermore, these residues and their by-products can be applied to non-agricultural soils; however, closing the loop within the agricultural domain based on a circular economy framework is a more compelling proposition. Effective planning in this regard likely necessitates the development of new regulatory frameworks in many countries.[117]

Achieving regenerative agriculture requires a deeper understanding of how soil additives like composts, manure, and biochar interact within soil ecosystems. Identifying soil parameters that dtermine whether these additives yield positive and sustainable outcomes under varying agricultural practices and environmental conditions is crucial. The exploration of such interactions and the dissemination of related knowledge should be integrated into agro-ecosystem management practices to aid climate change mitigation and adaptation efforts.

9. Conclusion

The issue of soil salinity arising from both natural processes and human activities poses significant challenges to soil health, agricultural productivity, and ecological sustainability. Geological phenomena, like weathering rocks and minerals, release salt into soil, establishing initial salinity levels in specific regions. Additionally, arid climates with low rainfall and high evaporation rates intensify salt accumulation due to inadequate leaching. Human interventions, particularly flawed irrigation practices with poor drainage and the use of high-salt irrigation water, further degrade soil quality, adversely impacting plant growth and ecosystem services. Soil salinity impedes plant water absorption, reduces nutrient uptake, and disrupts soil structure and microbial communities, ultimately diminishing agricultural yields and contaminating water resources.

Despite these challenges, the solubilization of LRC by bacteria is a promising solution for the remediation of saline soils. Bacterial action on LRC generates HOM, enhancing soil quality by improving structure and nutrient availability. These amendments help reduce soil salinity by facilitating the leaching of excess salts, thereby restoring soil health and productivity. Furthermore, the bacterial activity induced by solubilized coal contributes to the breakdown of pollutants, supporting soil remediation in saline environments. Leveraging solubilized LRC as an organic amendment offers an eco-friendly and cost-effective approach to restore and rehabilitate degraded landscapes, promoting agricultural productivity and ecosystem restoration. Moreover, bacterial solubilization of LRC offers an eco-friendly approach by harnessing natural microbial processes to degrade complex coal structures, releasing humified organic matter and bioactive substances that enhance soil quality and fertility. This method is cost-effective as it utilizes readily available microbial agents and does not require expensive chemical treatments, making it a sustainable solution for restoring soil health and productivity.

The current research explores the potential of various bacterial species to solubilize LRC. The investigation focused on identifying specific bacterial strains with enzymes capable of degrading complex coal structures. These studies summarized findings and illuminated diverse applications of bacterial solubilization for environmental remediation, bioenergy, and industrial processes. The findings indicate the vast potential of bacterial solubilization in addressing environmental challenges and offer sustainable solutions across sectors reliant on coal-derived products. Harnessing bacterial solubilization's enzymatic activities and metabolic pathways holds promise for innovative coal bioprocessing strategies and sustainable development, driving a transition toward eco-friendly solutions in diverse industries.

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The utilization of bacterial solubilization for treating LRC has been observed in diverse practical contexts, demonstrating its efficacy in the remediation of soil and the restoration of agricultural land. An instance of this is seen in a research endeavor in China, where coal-solubilizing bacteria were employed to address saline-alkali soil, resulting in enhanced soil composition, augmented organic material levels, and improved soil fecundity. This method not only decreased soil salinity but also stimulated plant development and agricultural output, underscoring the potential for bacterial solubilization in the rehabilitation of deteriorated soil and the revitalization of barren terrains.

A parallel illustration can be drawn from Australia, where scholars harnessed the bacterial solubilization of LRC to rectify polluted soil at a previous coal-gasification site. Through the application of solubilized LRC as an organic additive, they succeeded in elevating soil quality, diminishing contaminant concentrations, and facilitating the establishment of vegetation. This strategy not only decontaminated the area but also reinstated it as a functional ecosystem, highlighting the potential for bacterial solubilization in environmentally revitalizing undertakings.

Despite the notable advantages associated with the bacterial solubilization of LRC, there exist challenges and limitations that necessitate attention. One obstacle pertains to the scalability of the procedure, with the potential necessity of substantial resources and infrastructure for large-scale deployment. Furthermore, regulatory factors like environmental statutes and authorization prerequisites might impede the widespread adoption of this technology. Nevertheless, ongoing research and development efforts aim to surmount these constraints and enhance the efficiency and efficacy of bacterial solubilization of LRC for the sustainable management of soil and the environment.

In conclusion, it is imperative that future research in the field of bacterial solubilization of LRC should place a strong emphasis on the optimization of bacterial strains to significantly enhance the efficiency of solubilization processes. Moreover, there is an urgent need to explore innovative enzymatic pathways that could result in a more profound breakdown of the intricate structures present in coal. Furthermore, the integration of bioremediation methodologies with various other environmental remediation approaches, such as phytoremediation or the application of chemical treatments, holds great promise in yielding synergistic effects that could significantly enhance the overall outcomes of soil restoration efforts.

The pivotal role of collaboration among a diverse array of stakeholders, including researchers, industry professionals, and policymakers cannot be overstated because as it stands as a fundamental driver of innovation that is crucial for expediting the adoption of sustainable solutions. This collaborative framework facilitates the seamless translation of research discoveries into tangible applications that can be readily implemented, thereby ensuring that the solutions derived are effectively put into practice. Sustained investments in research and development are of paramount importance, as they are indispensable in tackling the myriad environmental challenges that we face today, ranging from soil salinity issues to degradation concerns. These investments are instrumental in promoting the advancement of sustainable development practices that not only safeguard ecosystems but also yield substantial benefits for human societies at large.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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