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Innovative Strategies for Soil Health Restoration in Saline-Alkali Environments: Leveraging Engineered Synthetic Microbial Communities (SynComs)

Yuanyuan Bu[1,2], Siyuan Gao[1,2], Shenkui Liu[3], Ruisheng Song[3]
1 Key Laboratory of Saline-Alkali Vegetation Ecology Restoration (Northeast Forestry University), Ministry of Education, Harbin, 150040, Heilongjiang, China
2 College of Life Sciences, Northeast Forestry University, Harbin, 150040, Heilongjiang, China
3 State Key Laboratory of Subtropical Silviculture, Zhejiang A & F University, Hangzhou, 311300, Zhejiang, China
Corresponding emails: yuanyuanbu@nefu.edu.cn; slpy@zafu.edu.cn
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Abstract Degradation of soil health in saline-alkali environments poses significant challenges to agricultural productivity and ecosystem sustainability. Traditional soil remediation methods often struggle to address the complex issues of salinity and alkalinity effectively. This study explores innovative strategies for restoring soil health using engineered synthetic microbial communities (SynComs). SynComs are custom-designed microbial consortia that can enhance nutrient cycling, promote plant growth, and improve soil structure. By introducing these beneficial microbial consortia into saline-alkali soils, SynComs offer a promising solution to mitigate adverse impacts and restore soil fertility. This paper reviews current research on the application of SynComs in soil health restoration, identifies key microbial functions and interactions, and discusses the potential applications and benefits of this integrated approach. The findings highlight the transformative potential of SynComs in developing sustainable strategies for soil health restoration, thereby contributing to agricultural resilience and ecosystem sustainability
Keywords Synthetic microbial communities; Saline-alkali environments; Soil health; Soil restoration; Agricultural resilience

Soil health is a crucial component of sustainable agriculture and ecosystem functionality. It encompasses the biological, chemical, and physical properties of soil, which collectively support plant growth, maintain environmental quality, and promote the health of plants and animals. Healthy soil is vital for nutrient cycling, water filtration, and providing habitats for various organisms, including beneficial microbes that enhance plant health and productivity (Shi et al., 2019; Wang et al., 2019; Zhang et al., 2021). Maintaining soil health not only ensures food security but also mitigates climate change and protects biodiversity.

Saline-alkali soils, characterized by high salt content and high pH, pose significant challenges to soil health, resulting in poor soil structure, reduced microbial activity, and nutrient imbalances. These issues hinder plant growth and decrease agricultural productivity. Salinization and alkalization are widespread global problems, affecting vast tracts of arable land and causing land degradation and economic losses (Qin et al., 2015; Liu et al., 2020; Zhang et al., 2021). High salinity and alkalinity disrupt soil microbial communities, further exacerbating soil health problems (Wang et al., 2020b).

Engineered synthetic microbial communities (SynComs) represent an innovative approach to soil restoration in saline-alkali environments. SynComs are specially designed microbial consortia aimed at enhancing nutrient availability, improving soil structure, and promoting plant growth under stress conditions. These consortia can include beneficial microbes resilient to high salinity and alkalinity, thus restoring soil health and productivity (Li et al., 2020). SynComs leverage advances in microbial ecology and biotechnology to create robust microbial networks that outperform native, less beneficial microbial populations, establishing a more favorable soil environment for plant growth (Qin et al., 2016; Sun et al., 2020).

This review summarizes the existing knowledge on the impact of saline-alkali conditions on soil health and microbial communities, reviews the latest advancements in SynComs development and application for soil remediation, identifies key microbial taxa and functional traits that contribute to the resilience and effectiveness of SynComs in saline-alkali soils, and discusses the challenges and future directions for researching and applying SynComs in agricultural practices. By integrating insights from multiple studies, this paper aims to explore the potential of engineered synthetic microbial communities (SynComs) in restoring soil health in saline-alkali environments, and to provide a roadmap for future research and practical applications to enhance soil health, improve crop productivity, and contribute to sustainable agricultural practices in saline-alkali environments.

1 Overview of Alkaline Soils

1.1 Characteristics and formation of saline-alkali soils

Saline-alkali soils are characterized by high concentrations of soluble salts and exchangeable sodium, which lead to elevated soil pH and poor soil structure. These soils typically form in arid and semi-arid regions where evaporation exceeds precipitation, causing salts to accumulate in the soil profile. The primary salts found in saline-alkali soils include sodium chloride, sodium sulfate, and sodium carbonate. The formation of these soils is often exacerbated by poor irrigation practices, inadequate drainage, and the use of saline water for irrigation (Shi et al., 2019).

1.2 Impact of salinity and alkalinity on soil health and crop productivity

High salinity and alkalinity adversely affect soil health by disrupting soil structure, reducing soil permeability, and impairing nutrient availability. These conditions lead to poor soil aeration and water infiltration, which in turn hinder root growth and microbial activity. Crop productivity is significantly reduced in saline-alkali soils due to osmotic stress, ion toxicity, and nutrient imbalances. For instance, high sodium levels can displace essential nutrients like potassium and calcium, leading to deficiencies that affect plant growth and yield (Cui et al., 2020; Lu et al., 2020). Additionally, salinity and alkalinity can alter the composition and function of soil microbial communities, further impacting soil health and plant productivity (Liu et al., 2020; Wang et al., 2020b).

1.3 Traditional methods of managing saline-alkali soils and their limitations

Traditional methods for managing saline-alkali soils include leaching, gypsum application, and the use of salt-tolerant crop varieties. Leaching involves the application of large volumes of water to flush salts from the root zone, but this method is often limited by water availability and the risk of groundwater contamination. Gypsum application helps to displace sodium ions with calcium ions, improving soil structure and reducing alkalinity. However, the effectiveness of gypsum is limited in soils with high levels of sodium carbonate, and its application can be cost-prohibitive (Huang et al., 2020; Wang et al., 2020b). The use of salt-tolerant crop varieties can provide some relief, but breeding programs have struggled to develop varieties that can thrive in highly saline-alkali conditions (Qin et al., 2016). These traditional methods often provide only temporary relief and do not address the underlying causes of soil salinization and alkalization, necessitating the exploration of more sustainable and innovative strategies (Zhou et al., 2022).

2 Engineered Synthetic Microbial Communities (SynComs)

2.1 Definition and principles of SynComs

Engineered Synthetic Microbial Communities (SynComs) are artificially designed consortia of microorganisms that are tailored to perform specific functions within an ecosystem. These communities are constructed using principles of synthetic biology and genetic engineering to enhance or introduce desired traits in microbial populations. The primary goal of SynComs is to leverage the synergistic interactions among different microbial species to achieve outcomes that are difficult to accomplish with single-species cultures (Figure 1). In the context of soil health restoration, SynComs can be designed to improve nutrient cycling, enhance plant growth, and mitigate the adverse effects of soil salinization and alkalization (Wang et al., 2019).

Arnault et al. (2024) conducted a series of meticulously designed experiments to explore and optimize the role of synthetic microbial communities (SynComs) in plant-microbe interactions. The study investigated the effects of mass and surface sterilization on seed colonization, the impact of soil and seed community coalescence on the rhizosphere, and the influence of SynCom composition on strain selection. By measuring the microbial community size at various stages from inoculation to the rhizosphere, the researchers assessed the effectiveness of SynComs. The study also constructed a phylogenetic tree of the 36 selected strains and illustrated the composition of the 13 SynComs, indicating their richness and the relative abundance of each strain in the original seed samples. Notably, seven strains were included in the study despite being undetected by the metabarcoding approach. This highlights the necessity of employing diverse methods, combining traditional microbiology with advanced genetic techniques, to gain a comprehensive understanding of microbial community dynamics and their application in sustainable agriculture.

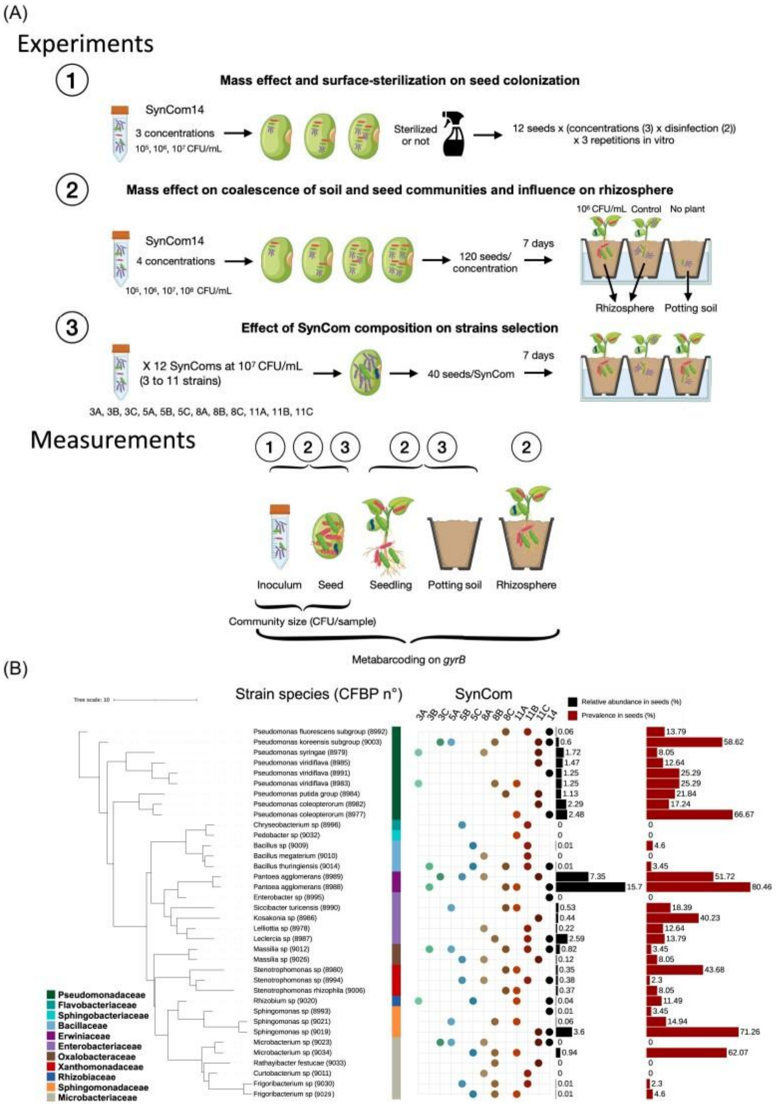

Figure 1 Design of the different experiments, strain selection, and SynCom compositions (Adopted from Arnault et al., 2024)

Image caption: A) Overview of the different experiments. B) Phylogenetic tree of the 36 strains selected and composition of the 13 SynComs. The number in SynCom names indicates the SynCom richness. Relative abundance and prevalence of each strain in the original seed samples are plotted on the right side. Seven strains were selected while they were not detected using the metabarcoding approach (Adopted from Arnault et al., 2024)

2.2 Techniques for engineering SynComs

The engineering of SynComs involves several advanced techniques, including:Synthetic Biology, This approach involves the design and construction of new biological parts, devices, and systems. Synthetic biology can be used to create novel metabolic pathways in microorganisms, enabling them to degrade pollutants or produce beneficial compounds. Genetic Modification: Genetic engineering techniques, such as CRISPR-Cas9, are employed to introduce specific genes into microbial genomes. These genes can confer traits such as salt tolerance, heavy metal resistance, or enhanced nutrient uptake. Metagenomics and Metatranscriptomics techniques allow for the comprehensive analysis of microbial communities and their functions. By understanding the native microbial communities in saline-alkali soils, researchers can identify key microbial players and their interactions, which can then be mimicked or enhanced in SynComs (Shi et al., 2019).

2.3 Advantages of using SynComs for soil health restoration

The use of SynComs offers several advantages for the restoration of soil health in saline-alkali environments, Enhanced microbial diversity and functionality (Figure 2), SynComs can be designed to include a diverse array of microbial species, each contributing unique functions that collectively enhance soil health. For instance, the inclusion of bacteria that produce plant growth-promoting hormones, degrade organic pollutants, or fix nitrogen can lead to improved soil fertility and structure. SynComs can be tailored to address specific soil health issues, such as salinity, alkalinity, or heavy metal contamination. By incorporating microorganisms that are specifically adapted to these stressors, SynComs can more effectively remediate contaminated soils (Zhang et al., 2021). SynComs offer a biological solution to soil health restoration that is sustainable and environmentally friendly. The use of naturally occurring or genetically modified microorganisms reduces the need for chemical inputs and minimizes the risk of secondary pollution.

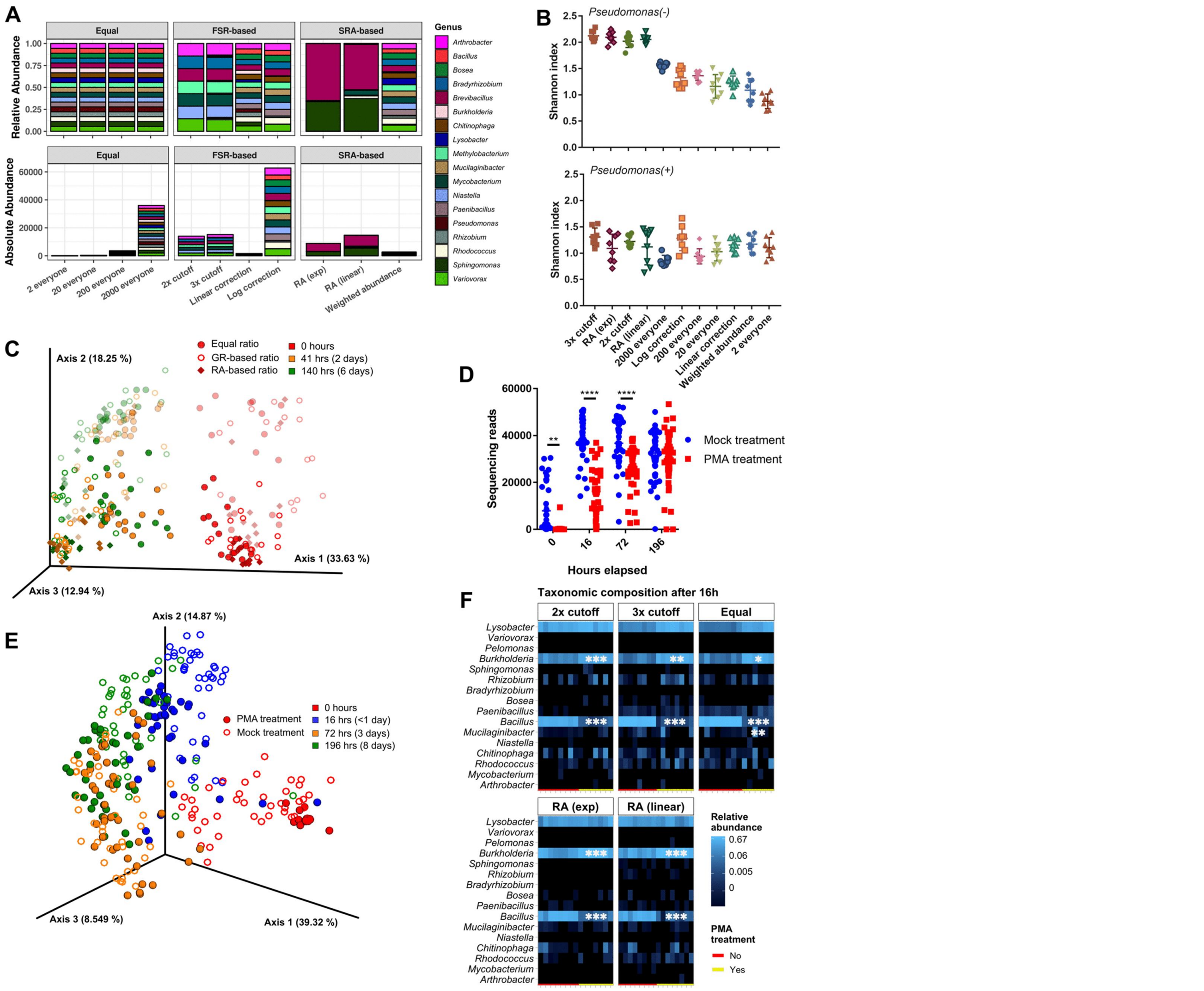

Figure 2 Maximizing SynCom diversity by adjusting the initial proportion of the community (Adopted from Coker et al., 2022)

Image caption: A) Representation of the 11 community starting ratios used in this study, including relative (top) and absolute (bottom) abundance. (B) Shannon diversity index for each community ratio, 2 and 6 days combined. (C) PCA of robust Aitchison distances between communities at different starting ratios. (D) Number of sequencing reads per sample passing quality filtering for PMA- and mock-treated conditions (Student's t-test; **, P < 0.01; ***, P < 0.001). (E) PCA of Aitchison distances between PMA- and mock-treated communities. (F) Heatmap of taxonomic composition of the five community ratios after 16 h of growth (Adopted from

Coker et al., 2022)

In summary, the strategic design and application of SynComs hold significant promise for the restoration of soil health in saline-alkali environments. By leveraging advanced techniques in synthetic biology and genetic engineering, SynComs can be tailored to enhance microbial diversity, target specific soil health issues, and provide sustainable solutions for soil remediation.

Coker et al. (2022) explored strategies to maximize the diversity of synthetic microbial communities (SynComs) by systematically adjusting the initial community proportions. The study utilized various starting ratios to analyze how these adjustments impact the overall microbial diversity and community structure. Shannon diversity index measurements combined at two and six days demonstrated the significant effects of initial proportions on community diversity. Principal Component Analysis (PCA) of robust Aitchison distances provided insights into the structural differences between communities at different starting ratios. Furthermore, the analysis compared sequencing reads under PMA and mock-treated conditions, revealing statistically significant differences. The taxonomic composition heatmap after 16 hours of growth highlighted the dynamic changes in community structure based on initial ratios. These findings underscore the importance of initial community composition in influencing SynCom diversity, offering valuable strategies for optimizing microbial communities for applications in agriculture and ecosystem management.

3 Mechanisms of SynComs in Soil Health Restoration

3.1 Biological pathways involved in the detoxification of saline-alkali soils

Synthetic microbial communities (SynComs) play a crucial role in the detoxification of saline-alkali soils through various biological pathways. One significant mechanism is the enhancement of antioxidant enzyme activities, which helps in mitigating oxidative stress caused by high salinity and alkalinity. For instance, the overexpression of specific genes such as ChbZIP1 in plants has been shown to upregulate antioxidant enzymes like GPX1, DOX1, and CAT2, thereby enhancing the plant's tolerance to alkali stress (Qu et al., 2021). Additionally, SynComs can influence the microbial community structure, promoting the growth of haloalkaliphilic taxa that are better adapted to saline-alkali conditions, thus aiding in the detoxification process (Wang et al., 2019).

3.2 Enhancement of nutrient cycling and soil structure by SynComs

SynComs contribute significantly to nutrient cycling and the improvement of soil structure in saline-alkali environments. The application of organic amendments such as vermicompost and humic acid fertilizers has been shown to enhance soil aggregate stability and microstructure, which in turn improves soil permeability and salt leaching (Liu et al., 2020). These amendments also stimulate the microbial community involved in nitrogen cycling, increasing the abundance of nitrifying bacteria and reducing nitrogen losses through denitrification processes. Furthermore, SynComs can enhance enzyme activities such as catalase, urease, and alkaline phosphatase, which are crucial for nutrient cycling and overall soil health.

3.3 Interaction between SynComs and native soil microbiota

The interaction between SynComs and native soil microbiota is a key factor in the successful restoration of saline-alkali soils. SynComs are designed to complement and enhance the existing microbial communities, promoting beneficial interactions that improve soil health. For example, SynComs can enhance the diversity and richness of native bacterial communities, leading to a more resilient and stable soil microbiome (Shi et al., 2019). Additionally, the introduction of SynComs can alter the microbial network interactions, strengthening the adaptability of the soil microbiome to saline-alkali stress (Martins et al., 2023). This synergistic interaction between SynComs and native microbiota is essential for the long-term sustainability of soil health restoration efforts.

3.4 Potential for long-term soil health improvement

The potential for long-term soil health improvement through the use of SynComs is promising, given their ability to provide consistent and stable benefits under various environmental conditions. SynComs are engineered to possess traits that ensure robust colonization and persistence in the soil, which is crucial for maintaining their beneficial effects over time (Souza et al., 2020; Martins et al., 2023). Moreover, the use of computational methods such as machine learning can optimize the selection and combination of microbial species in SynComs, enhancing their effectiveness in promoting plant health and soil resilience. By leveraging these innovative strategies, SynComs offer a sustainable solution for the restoration and maintenance of soil health in saline-alkali environments.

4 Integrative Approaches to SynCom Design and Application

4.1 Selection of microbial strains and engineering for specific soil health functions

The selection of microbial strains for SynComs in saline-alkali environments is crucial for enhancing soil health and plant growth. Studies have shown that certain bacterial and fungal communities exhibit higher tolerance and resilience to saline-alkali stress, making them ideal candidates for SynComs. For instance, keystone bacteria and fungi identified in various saline-alkali soils, such as those in Inner Mongolia, demonstrate potential adaptability and benefits in restoring soil health (Zhang et al., 2021). Additionally, the use of microbial inoculums, such as those involving T. ambiguum Bieb., has shown significant improvements in soil fertility and reduction in salinity and alkalinity (Li et al., 2021). Engineering these microbial strains to enhance their specific functions, such as nitrogen cycling and salt tolerance, can further improve their efficacy in SynComs.

4.2 Optimization of SynCom composition and diversity for saline-alkali environments

Optimizing the composition and diversity of SynComs is essential for their success in saline-alkali environments. Research indicates that a diverse microbial community can better withstand environmental stresses and improve soil health. For example, the combination of organic amendments, such as farm manure and desulfurization gypsum, has been shown to increase bacterial community richness and enzyme activities, thereby enhancing soil quality. Similarly, the addition of vermicompost and humic acid fertilizer has been found to improve soil aggregate stability and microstructure, leading to better salt leaching and nitrogen retention (Liu et al., 2020). By carefully selecting and combining microbial strains that complement each other, SynComs can be tailored to address the specific challenges of saline-alkali soils (Qin et al., 2016).

4.3 Integration of SynComs with other soil management practices (e.g., organic amendments, crop rotation)

Integrating SynComs with other soil management practices can amplify their benefits and contribute to sustainable soil health restoration. Organic amendments, such as farm manure and straw, have been shown to significantly improve microbial diversity and soil organic carbon content, which are critical for soil health (Liu et al., 2023) Additionally, practices like crop rotation and the use of cover crops can enhance the effectiveness of SynComs by providing a continuous supply of organic matter and promoting beneficial microbial interactions (Qin et al., 2016). For instance, the combination of microbial inoculums with terraced landscape design has proven effective in reducing salinity and alkalinity while improving soil fertility in oil-polluted areas (Li et al., 2021). By integrating SynComs with these complementary practices, a holistic approach to soil health restoration in saline-alkali environments can be achieved.

5 Field Applications and Performance Evaluation

5.1 Overview of methodologies for field application of SynComs

The application of engineered synthetic microbial communities (SynComs) in saline-alkali soil restoration involves several methodologies aimed at enhancing soil health and crop productivity. One common approach is the amendment of soils with organic and inorganic materials that support microbial activity and diversity. For instance, the use of farm manure, desulfurization gypsum, and sandy soil has been shown to significantly improve soil pH and enzyme activities, thereby fostering a conducive environment for microbial communities (Shi et al., 2019). Additionally, the incorporation of vermicompost and humic acid fertilizers has been found to improve soil aggregate stability and microstructure (Liu et al., 2020).

5.2 Key field trials and case studies of SynComs in saline-alkali soil restoration

Several field trials have demonstrated the efficacy of SynComs in restoring saline-alkali soils. A notable study conducted over seven years revealed that amendments with farm manure, desulfurization gypsum, and a mixture of these materials significantly increased enzyme activities and bacterial community diversity, which are critical indicators of soil health. Another study highlighted the role of vermicompost and humic acid fertilizers in enhancing soil structure and microbial community composition, leading to improved salt leaching and reduced nitrogen losses (Liu et al., 2020). Furthermore, research in various regions of Inner Mongolia identified keystone microbial taxa that exhibit high tolerance and resilience to saline-alkali stress, suggesting their potential in SynCom formulations for soil restoration (Zhang et al., 2021).

5.3 Criteria and metrics for evaluating the performance of SynComs in field conditions

Evaluating the performance of SynComs in field conditions involves several criteria and metrics. Key indicators include soil pH, enzyme activities (such as catalase, urease, alkaline phosphatase, and cellulase), and microbial community diversity and richness. Soil aggregate stability and microstructure improvements, such as increased porosity and effective permeability, are also critical metrics, as they directly influence salt leaching and nutrient cycling (Liu et al., 2020). Additionally, the presence and abundance of keystone microbial taxa, which play disproportionate ecological roles in stress resistance and soil health, serve as important markers for the success of SynCom applications (Wang et al., 2020a). These metrics collectively provide a comprehensive assessment of the effectiveness of SynComs in restoring saline-alkali soils.

6 Case Studies

6.1 Detailed analysis of specific field trials and their outcomes

Field trials across various saline-alkaline environments have demonstrated the potential of engineered synthetic microbial communities (SynComs) in restoring soil health. For instance, a study conducted in Inner Mongolia revealed that microbial assemblages in saline-alkaline soils are primarily driven by soluble salt ion components rather than salinity itself. This study identified keystone bacteria and fungi that could potentially adapt to and restore saline-alkaline soils by enhancing plant growth and soil functions (Zhang et al., 2021). Another field trial in Northern China tested the effects of bio-fertilizer and rotten straw amendments on oat productivity in saline-alkaline soils. The combined amendment treatment significantly improved oat yields, reduced soil pH, and increased soil salt content, demonstrating the effectiveness of organic amendments in such challenging environments (Lu et al., 2020). Similarly, a five-year field experiment with Miscanthus cultivation showed substantial improvements in soil fertility and reductions in soil salinity and pH, highlighting the role of beneficial bacteria in soil desalinization and nutrient cycling (Xu et al., 2021).

6.2 Success stories and lessons learned

Several success stories have emerged from these field trials. The use of vermicompost and humic acid fertilizer in saline-alkaline soils improved soil aggregate stability and microstructure, leading to enhanced salt leaching and reduced nitrogen losses. This approach also increased the abundance of beneficial aerobic heterotrophs, which play a crucial role in nutrient cycling and soil health (Liu et al., 2020). In the Yellow River Delta, the combination of straw and desulfurization gypsum significantly improved soil organic carbon and microbial biomass, while reducing soil pH and exchangeable sodium percentage. This integrated strategy proved effective in enhancing soil health and microbial diversity (Liu et al., 2023). Another notable success was observed in Daqing, where the use of T. ambiguum Bieb. and microbial inoculums in a terraced landscape design led to a 94.7% removal rate of oily substances and significant reductions in soil salinity and alkalinity (Li et al., 2021).

6.3 Limitations and areas for improvement

Despite these successes, there are limitations and areas for improvement in the application of SynComs for soil health restoration. One major limitation is the variability in microbial community responses to different soil types and environmental conditions.In Cd-contaminated soils, soil bacteria were more responsive to saline-alkaline stress than fungi, indicating the need for tailored microbial solutions for different soil conditions (Wang et al., 2019). Additionally, while the combination of organic amendments and microbial inoculums has shown promise, the long-term sustainability and scalability of these approaches need further investigation. More extensive multi-location trials are required to assess the consistency of these improvements across diverse environments (Xu et al., 2021). Furthermore, understanding the specific roles and interactions of microbial taxa in saline-alkaline soils can help refine SynCom formulations to enhance their effectiveness and resilience.

7 Challenges and Limitations

7.1 Technical challenges in engineering and deploying SynComs in saline-alkali soils

Engineering and deploying synthetic microbial communities (SynComs) in saline-alkali soils present several technical challenges. One significant issue is ensuring the stability and colonization of SynComs in such harsh environments. The dynamic nature of microbial communities, influenced by horizontal gene transfer and mutations, can lead to changes over time, making it difficult to maintain the desired plant phenotype stability (Martins et al., 2023). Additionally, the high salinity and alkalinity of these soils can inhibit microbial activity and survival, complicating the establishment of SynComs (Liu et al., 2020). The complexity of designing SynComs that can thrive under these conditions while providing consistent benefits to plant health is another technical hurdle (Souza et al., 2022).

7.2 Ecological and environmental considerations

The introduction of SynComs into saline-alkali soils must consider the ecological balance and potential environmental impacts. The interactions between introduced SynComs and native microbial communities can lead to unforeseen consequences, such as the displacement of beneficial native microbes or the proliferation of harmful ones (Pradhan et al., 2022). Moreover, the ecological theories suggest that plant-associated microbial communities are not randomly assembled but follow specific assembly rules, which can be disrupted by the introduction of SynComs (Martins et al., 2023). The potential for SynComs to alter soil enzyme activities and nutrient cycling processes also needs careful evaluation to avoid negative impacts on soil health and plant growth.

7.3 Economic and scalability issues

The economic feasibility and scalability of deploying SynComs in saline-alkali soils are significant concerns. The cost of developing and producing SynComs, including the necessary research and development, can be high. Additionally, scaling up the production of SynComs to meet agricultural demands poses logistical challenges (Pradhan et al., 2022). The need for specialized equipment and expertise to apply SynComs effectively in the field further adds to the costs. Ensuring that the benefits of SynComs outweigh these costs is crucial for their widespread adoption (Souza et al., 2020).

7.4 Regulatory and safety concerns

Regulatory and safety concerns are paramount when introducing SynComs into agricultural systems. The potential risks associated with the release of genetically engineered microbes into the environment must be thoroughly assessed. Regulatory frameworks need to be established to ensure that SynComs are safe for the environment and human health (Li et al., 2021). Additionally, public perception and acceptance of using engineered microbes in agriculture can influence regulatory decisions and the adoption of SynComs. Addressing these concerns through transparent risk assessments and effective communication with stakeholders is essential.

8 Future Directions and Perspectives

8.1 Emerging trends and technologies in SynCom engineering

The field of synthetic microbial communities (SynComs) is rapidly evolving, with several emerging trends and technologies poised to revolutionize soil health restoration in saline-alkali environments. One significant trend is the integration of computational methods, such as machine learning and artificial intelligence, to screen and identify beneficial microbes. These technologies enhance the process of determining the optimal combination of microbes for desired plant phenotypes, thereby improving the stability and effectiveness of SynComs (Liu et al., 2020). Additionally, advancements in high-throughput sequencing technologies allow for a more detailed understanding of microbial community structures and their interactions with plants, which is crucial for designing effective SynComs (Pradhan et al., 2022).

8.2 Integration of SynComs into broader soil health management frameworks

Integrating SynComs into broader soil health management frameworks involves combining them with traditional soil amendments and other bioremediation strategies. For instance, the use of organic manure and desulfurization gypsum has been shown to improve bacterial community richness and enzyme activities in saline-alkali soils, suggesting that these amendments could be used in conjunction with SynComs to enhance soil health. Moreover, the adaptability of microbial communities to saline-alkali stress, as demonstrated by their structural reorganization and network interactions, indicates that SynComs could be tailored to specific soil conditions to maximize their effectiveness (Shi et al., 2019; Lu et al., 2020). This holistic approach could lead to more sustainable and resilient soil health management practices.

8.3 Long-term vision and potential breakthroughs in SynCom-based soil restoration

The long-term vision for SynCom-based soil restoration includes the development of highly specialized microbial consortia that can not only survive but thrive in extreme saline-alkali conditions. Future research should focus on identifying keystone microbial taxa that play disproportionate ecological roles in enhancing soil health and plant resilience (Lu et al., 2020). Additionally, the potential for SynComs to be used in combination with innovative landscape designs, such as terraced landscapes, offers promising avenues for large-scale soil restoration projects (Pradhan et al., 2022). Ultimately, breakthroughs in SynCom engineering could lead to the creation of self-sustaining microbial ecosystems that continuously improve soil health and support robust agricultural productivity in saline-alkali environments.

By leveraging these emerging trends, integrating SynComs into broader soil health frameworks, and focusing on long-term breakthroughs, the potential for SynCom-based soil restoration in saline-alkali environments is immense. Continued research and technological advancements will be crucial in realizing this potential and achieving sustainable soil health restoration.

9 Concluding Remarks

In this systematic study, we explored innovative strategies for restoring soil health in saline-alkali environments, focusing on the potential of engineered synthetic microbial communities (SynComs). This paper highlights several key findings from recent research. The microbial composition in saline-alkali soils is significantly affected by soluble salt ions, with fungal communities showing greater tolerance and resilience compared to bacterial communities.

The use of biofertilizers and organic amendments, such as decomposed straw, has been shown to alter rhizosphere bacterial communities and improve crop productivity in saline-alkali soils. Phytoremediation using plants like Miscanthus can enhance soil properties and microbial community structure, thereby reducing soil salinity and increasing soil fertility. Amendments such as earthworm castings and humic acid fertilizers can improve soil aggregate stability, enhance salt leaching, and inhibit nitrogen loss. Combining straw with desulfurized gypsum also effectively improves soil chemical properties and microbial diversity.

Additionally, integrating plant microbial inoculants in terraced landscapes has shown promising results in reducing soil salinity and alkalinity. These findings are significant for researchers, policymakers, and land managers. Researchers can use insights into microbial community dynamics and the effectiveness of various amendments to develop targeted soil restoration strategies. Policymakers can use this knowledge to formulate guidelines and policies that promote sustainable agricultural practices and soil health management in saline-alkali regions. Land managers can adopt these innovative strategies to improve soil fertility, enhance crop yields, and mitigate the adverse effects of soil salinization and alkalization.

Despite the encouraging results, further research is needed to optimize the application of SynComs and other amendments in various saline-alkali environments. Interdisciplinary collaboration among soil scientists, microbiologists, agronomists, and environmental engineers is crucial for developing comprehensive and scalable solutions. Future research should focus on long-term field trials, the ecological impact of SynComs, and the economic feasibility of these restoration strategies. By fostering collaboration and continuous research, we can advance the understanding and implementation of effective soil health restoration techniques in saline-alkali environments.

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Conflict of Interest Disclosure

The authors declare no competing interests.

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