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Engineered SynComs for Climate-Resilient Agriculture: Field Trials and Performance Evaluation

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Abstract Engineered SynComs, designed to enhance plant growth and yield under a variety of abiotic stresses, have shown considerable potential in promoting plant growth and yield in harsh climates, providing a promising tool for climate-resilient agriculture. Including drought, salinity and extreme temperatures. This research synthesizes the results of multiple field trials conducted in a variety of agricultural environments under different climatic conditions. Field trials showed that SynComs significantly improved crop performance under various environmental stress conditions, with key observations including increased biomass, root length and yield, as well as enhanced stress resistance. Specifically, plants treated with SynCom showed higher resistance, such as maintaining higher chlorophyll levels under saline-alkali stress and reducing oxidative damage at extreme temperatures. This study hopes to assess the development and field performance of engineered synthetic microbial communities (SynComs) designed for climate-resilient agriculture, with a focus on their ability to improve plant health, yield, and stress resistance to fully utilize their potential and ensure consistent performance across crops and environmental conditions.

Keywords Engineered SynComs; Climate resilience; Crop yield; Environmental stress; Field trials

1 Introduction

Climate change poses a significant threat to global agriculture, affecting crop productivity and food security. Variations in annual rainfall, average temperature, heat waves, and changes in pest and microbial populations are some of the critical factors influenced by climate change that adversely impact agricultural systems (Raza et al., 2019). These environmental stressors lead to biotic and abiotic stresses, which compromise crop yields and threaten food security worldwide. The urgency to develop climate-resilient agricultural practices has never been greater, as traditional farming methods struggle to cope with the rapidly changing climate (Raza et al., 2019).

Engineered synthetic microbial communities (SynComs) have emerged as a promising solution to enhance crop resilience and productivity under adverse environmental conditions. SynComs are designed consortia of microorganisms that are tailored to perform specific beneficial functions for plants, such as promoting growth, enhancing nutrient acquisition, and providing resistance against pathogens (Souza et al., 2020; Marín et al., 2021; Martins et al., 2023). By leveraging advances in microbial ecology, genetics, and computational methods, researchers can identify and assemble microbial communities that offer stable and effective inoculants for agriculture (Souza et al., 2020; Martins et al., 2023). These communities are not randomly assembled but are structured based on ecological theories and functional screening to ensure they thrive under environmental stressors and maintain long-term stability (Wang et al., 2021; Martins et al., 2023).

This systematic study aims to evaluate the performance of engineered SynComs in field trials and their potential to create climate-resilient agricultural systems. By reviewing recent advances and experimental outcomes, this study seeks to provide a comprehensive understanding of how SynComs can be effectively utilized to enhance crop resilience against climate-induced stresses. The significance of this study lies in its potential to bridge knowledge gaps and offer practical insights into the design and application of SynComs in agriculture. By highlighting successful case studies and identifying challenges, this research hopes to contribute to the development of sustainable agricultural practices that can withstand the impacts of climate change.

In summary, the integration of SynComs into agricultural practices represents a promising strategy to mitigate the adverse effects of climate change on crop production. This study will explore the current state of SynCom research, evaluate their performance in field trials, and discuss their potential to revolutionize climate-resilient agriculture.

2 Overview for Engineered SynComs

2.1 Definition and characteristics of engineered SynComs

Engineered Synthetic Microbial Communities (SynComs) are carefully designed consortia of microorganisms that are tailored to perform specific functions beneficial to plant health and productivity. These communities are not naturally occurring but are constructed using principles from microbial ecology and genetics to enhance plant resilience and growth under various environmental conditions (Souza et al., 2020; Shayanthan et al., 2022). SynComs are characterized by their ability to form stable, functional associations with plant hosts, often leading to improved plant performance through mechanisms such as enhanced nutrient uptake, stress tolerance, and disease resistance (Souza et al., 2020; Pradhan et al., 2022).

2.2 Methods for engineering SynComs

The engineering of SynComs involves several advanced methodologies, including synthetic biology and genetic modification. Synthetic biology allows for the precise assembly of microbial consortia by selecting and combining microbial species with desired traits (Souza et al., 2020; Martins et al., 2023). Genetic modification techniques can be used to enhance specific functions of these microbes, such as nutrient solubilization or stress resistance (Shayanthan et al., 2022). Additionally, computational methods, including machine learning and artificial intelligence, are increasingly employed to screen and identify beneficial microbes and to determine the optimal combinations of microbes for achieving desired plant phenotypes (Souza et al., 2020; Martins et al., 2023). These approaches ensure that the engineered SynComs are robust, stable, and capable of performing their intended functions under field conditions.

2.3 Advantages of using engineered SynComs over traditional agricultural methods

Engineered SynComs offer several advantages over traditional agricultural methods. Firstly, they provide a sustainable alternative to chemical fertilizers and pesticides, reducing the environmental impact of agriculture (Pradhan et al., 2022; Shayanthan et al., 2022). SynComs can enhance plant resilience to abiotic stresses such as drought and salinity, thereby improving crop productivity under adverse conditions (Armanhi et al., 2021; Shayanthan et al., 2022). They also promote plant health by enhancing nutrient uptake and suppressing soil-borne pathogens through competitive exclusion and the production of antimicrobial compounds (Pradhan et al., 2022; Martins et al., 2023). Furthermore, the use of SynComs can lead to more consistent and reliable outcomes compared to traditional single-strain inoculants, as the synergistic interactions within the microbial community contribute to greater stability and functionality (Shayanthan et al., 2022; Martins et al., 2023). Overall, the integration of engineered SynComs into agricultural practices holds great promise for achieving climate-resilient and sustainable crop production.

3 Climate-Resilient Agriculture

3.1 Definition and importance of climate-resilient agriculture

Climate-resilient agriculture refers to farming practices that are designed to withstand the adverse effects of climate change while maintaining or improving productivity. This approach is crucial for ensuring food security in the face of increasing environmental stressors such as drought, extreme temperatures, and soil degradation. The importance of climate-resilient agriculture lies in its potential to sustain agricultural productivity and livelihoods, reduce vulnerability to climate variability, and enhance the adaptive capacity of farming systems (Pradhan et al., 2022; Shayanthan et al., 2022).

3.2 Challenges faced by traditional agriculture under climate change

Traditional agricultural practices are increasingly challenged by the impacts of climate change. These challenges include:

Increased incidence of pests and diseases: Climate change can alter the distribution and lifecycle of pests and pathogens, leading to more frequent and severe outbreaks (Pradhan et al., 2022).

Water scarcity: Changes in precipitation patterns and increased evaporation rates can lead to water shortages, affecting crop yields and quality (Shayanthan et al., 2022).

Soil degradation: Extreme weather events and unsustainable farming practices can lead to soil erosion, loss of fertility, and reduced agricultural productivity (Pradhan et al., 2022).

Unpredictable weather patterns: Variability in weather conditions makes it difficult for farmers to plan and manage their crops effectively, leading to reduced yields and increased risk of crop failure (Jin et al., 2023).

3.3 Role of SynComs in enhancing climate resilience

Synthetic microbial communities (SynComs) offer a promising solution to enhance the resilience of agricultural systems to climate change. SynComs are designed consortia of microorganisms that can provide specific benefits to plants, such as improved growth, disease resistance, and stress tolerance. The role of SynComs in enhancing climate resilience includes:

Improving plant health and productivity: SynComs can enhance plant growth by promoting nutrient uptake, producing growth hormones, and protecting plants from pathogens (Yin et al., 2022; Martins et al., 2023).

Enhancing stress tolerance: SynComs can help plants withstand abiotic stresses such as drought, salinity, and extreme temperatures by modulating plant stress responses and improving water and nutrient use efficiency (Souza et al., 2020; Pradhan et al., 2022).

Stabilizing soil microbiomes: By introducing beneficial microbes, SynComs can help maintain a stable and functional soil microbiome, which is crucial for soil health and plant productivity under changing environmental conditions (Shayanthan et al., 2022; Bu et al., 2024).

Reducing dependence on chemical inputs: The use of SynComs can reduce the need for chemical fertilizers and pesticides, leading to more sustainable and environmentally friendly farming practices (Pradhan et al., 2022).

In summary, SynComs represent a cutting-edge approach to developing climate-resilient agricultural systems by leveraging the beneficial traits of microbial communities to support plant health and productivity under adverse environmental conditions. This innovative strategy holds great promise for addressing the challenges posed by climate change and ensuring sustainable agricultural production in the future.

4 Field Trials of Engineered SynComs

4.1 Overview of field trial methodologies

Field trials of engineered synthetic microbial communities (SynComs) are essential for evaluating their effectiveness in enhancing crop resilience under various environmental conditions. These trials typically involve the following methodologies:

Selection and design of SynComs: SynComs are designed based on functional screening of microbial strains isolated from plant-associated environments. The selection criteria include traits such as nutrient acquisition, disease suppression, and stress tolerance (Souza et al., 2020; Wang et al., 2021; Yin et al., 2022).

Experimental setup: Field trials are conducted in controlled plots where crops are inoculated with SynComs. Control plots without SynCom inoculation are maintained for comparison. The trials are designed to simulate real agricultural conditions, including varying levels of nutrient availability and environmental stressors (Armanhi et al., 2021; Wang et al., 2021).

Data collection and analysis: Various parameters such as plant growth, yield, nutrient uptake, and resistance to pathogens are measured. Advanced techniques like RNA sequencing and real-time phenotyping platforms are used to monitor plant responses and microbial colonization (Armanhi et al., 2021; Wang et al., 2021).

4.2 Key field trials conducted on SynComs for climate-resilient agriculture

Several significant field trials have been conducted to evaluate the performance of SynComs in promoting climate-resilient agriculture:

Soybean field trials: In a study, three SynComs were constructed from 1893 microbial strains isolated from soybean roots. These SynComs significantly enhanced plant growth and nutrient acquisition under both nutrient-deficient and sufficient conditions. Field trials showed that SynComs increased soybean yield by up to 36.1% at two different sites (Wang et al., 2021).

Wheat field trials: Ten SynComs derived from wheat rhizosphere bacteria were tested for their ability to protect wheat against the soilborne fungal pathogen Rhizoctonia solani AG8. Seven SynComs successfully reduced root rot disease, although they were not more effective than single strains in some cases (Yin et al., 2022).

Maize field trials: A SynCom containing plant-beneficial bacteria was tested on three commercial maize hybrids under drought stress conditions. The SynCom inoculation reduced yield loss, modulated physiological traits, and improved water usage efficiency. The high-resolution temporal data collected revealed the SynCom's impact on maize resilience to drought (Armanhi et al., 2021).

4.3 Parameters and metrics used for evaluating field trial performance

The performance of SynComs in field trials is evaluated using a variety of parameters and metrics:

Plant growth and yield: Measurements include plant height, biomass, and crop yield. These metrics provide direct evidence of the SynCom's impact on plant productivity (Armanhi et al., 2021; Wang et al., 2021).

Nutrient uptake: The efficiency of nutrient acquisition, particularly nitrogen (N) and phosphorus (P), is assessed through soil and plant tissue analyses. Enhanced nutrient uptake indicates improved plant health and growth (Wang et al., 2021).

Disease resistance: The incidence and severity of diseases, particularly those caused by soilborne pathogens, are monitored. The effectiveness of SynComs in suppressing disease is a critical metric for evaluating their potential as biocontrol agents (Yin et al., 2022).

Physiological traits: Parameters such as leaf temperature, turgor pressure, and sap flow are measured to assess plant physiological responses to environmental stressors. These traits help in understanding the mechanisms through which SynComs confer stress resilience (Armanhi et al., 2021).

Microbial colonization: The persistence and colonization efficiency of SynComs in the plant rhizosphere are evaluated using microbiome profiling techniques. Stable colonization is essential for the long-term effectiveness of SynComs (Armanhi et al., 2021).

By systematically evaluating these parameters, researchers can determine the potential of engineered SynComs to enhance crop resilience and productivity under climate stress conditions.

5 Performance Evaluation of SynComs

5.1 Criteria for performance evaluation

The performance of synthetic microbial communities (SynComs) in agriculture can be evaluated using several key criteria:

Crop yield: One of the primary metrics for evaluating the effectiveness of SynComs is the increase in crop yield. This includes measuring the quantity and quality of the produce harvested from plants treated with SynComs compared to control groups (Bailey-Serres et al., 2019; Souza et al., 2020; Sai et al., 2022).

Soil health: Soil health is assessed by examining various parameters such as nutrient content, microbial diversity, and soil structure. The ability of SynComs to enhance soil fertility and maintain a healthy soil microbiome is crucial for sustainable agriculture (Guzmán et al., 2021; Sai et al., 2022).

Resistance to stressors: Evaluating the resilience of crops to biotic (e.g., pests and pathogens) and abiotic (e.g., drought, salinity, heat) stressors is essential. SynComs should help plants withstand these stressors better than traditional methods (Abdelrahman et al., 2017; Armanhi et al., 2021; Guzmán et al., 2021).

Plant physiological traits: Monitoring changes in plant physiological traits such as leaf temperature, turgor pressure, and sap flow can provide insights into how SynComs influence plant health and stress responses (Armanhi et al., 2021).

5.2 Results and findings from field trials

Field trials have demonstrated the potential of SynComs to improve crop performance under various conditions:

Yield improvement: Studies have shown that SynCom-inoculated plants often exhibit higher yields compared to those treated with traditional methods. For instance, maize plants inoculated with a synthetic bacterial community showed significant yield improvements under drought stress conditions (Armanhi et al., 2021; Han, 2024).

Enhanced soil health: SynComs have been found to improve soil health by increasing microbial diversity and nutrient availability. This, in turn, supports better plant growth and resilience (Guzmán et al., 2021; Sai et al., 2022).

Stress resistance: SynComs have been effective in enhancing plant resistance to both biotic and abiotic stressors. For example, SynComs have been shown to reduce yield loss and improve recovery rates in plants subjected to drought stress (Abdelrahman et al., 2017; Armanhi et al., 2021).

Physiological benefits: Field trials have recorded beneficial changes in plant physiological traits, such as lower leaf temperatures and reduced turgor loss, indicating better water usage and stress management in SynCom-treated plants (Armanhi et al., 2021).

5.3 Comparative analysis of SynComs versus traditional methods

Comparative studies between SynComs and traditional agricultural methods highlight several advantages of using SynComs:

Higher efficiency: SynComs have been shown to be more effective in promoting plant growth and resilience compared to traditional single-strain inoculants. This is due to the synergistic interactions within the microbial community that enhance overall plant health (Souza et al., 2020; Sai et al., 2022).

Sustainability: Unlike chemical fertilizers and pesticides, SynComs offer a more sustainable approach to agriculture by reducing dependency on synthetic inputs and improving soil health (Guzmán et al., 2021; Sai et al., 2022).

Adaptability: SynComs can be tailored to specific crops and environmental conditions, making them more versatile and effective in diverse agricultural settings (Souza et al., 2020; Guzmán et al., 2021).

Stress management: SynComs provide better protection against a combination of stressors, which is increasingly important in the context of climate change. Traditional methods often fail to address the complex interactions between multiple stress factors (Abdelrahman et al., 2017; Rivero et al., 2021).

In conclusion, the use of SynComs in agriculture presents a promising alternative to traditional methods, offering enhanced crop yields, improved soil health, and greater resilience to environmental stressors. The ongoing field trials and research continue to validate the efficacy and benefits of SynComs in creating climate-resilient agricultural systems.

6 Case Studies

6.1 Detailed analysis of specific field trials and their outcomes

In recent years, several field trials have been conducted to evaluate the effectiveness of engineered synthetic microbial communities (SynComs) in enhancing crop resilience under various environmental conditions. One notable study involved the application of SynComs derived from rhizosphere soil to protect wheat against the soilborne fungal pathogen Rhizoctonia solani AG8 (Figure 1). This study created ten different SynComs from 14 bacterial strains, and seven of these SynComs successfully protected wheat from infection, although they were not more effective than single strains in reducing root rot disease (Yin et al., 2022).

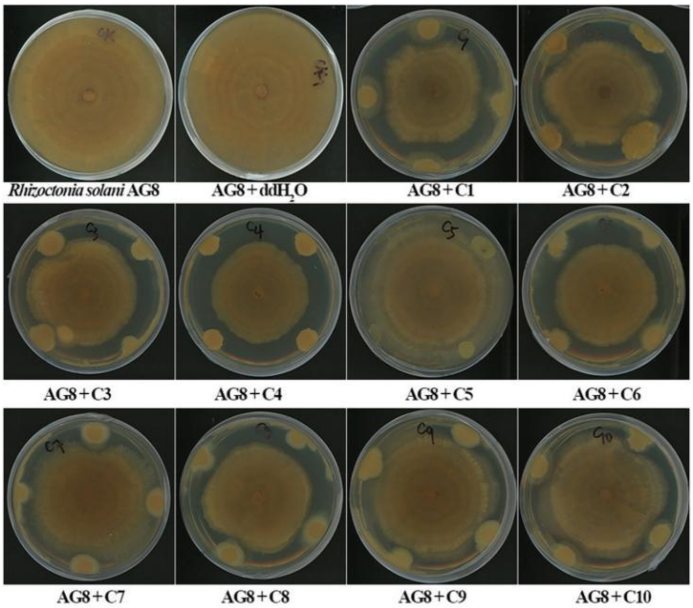

Figure 1 The inhibition of synthetic microbial communities (SynComs) on the growth of *Rhizoctonia solani* AG8 in dual-culture assay (Adopted from Yin et al., 2022)

Image caption: C1: SynCom 1; C2: SynCom 2; C3: SynCom 3; C4: SynCom 4; C5: SynCom 5; C6: SynCom 6; C7: SynCom 7; C8: SynCom 8; C9: SynCom 9; C10: SynCom 10 (Adopted from Yin et al., 2022)

Another significant trial focused on designing SynComs with microorganisms possessing traits for robust colonization and specific beneficial functions for plants. This approach utilized computational methods, including machine learning and artificial intelligence, to screen and identify beneficial microbes, ultimately improving the process of determining the best combination of microbes for desired plant phenotypes (Figure 2) (Souza et al., 2020).

6.2 Success stories and lessons learned

The field trials have yielded several success stories, demonstrating the potential of SynComs in enhancing crop resilience. For instance, the study on wheat protection against Rhizoctonia solani AG8 highlighted the ability of SynComs to inhibit the growth of the pathogen through the production of volatiles (Figure 3) and cell-free supernatants (Figure 4) from specific bacterial strains (Yin et al., 2022).

Additionally, the use of computational methods to design SynComs has shown promise in delivering stable and effective inoculants tailored to specific plant needs, thereby enhancing crop performance under stressful conditions (Souza et al., 2020). These successes underscore the importance of integrating microbial ecology and genetics in the design of SynComs and leveraging advanced computational tools to optimize microbial combinations.

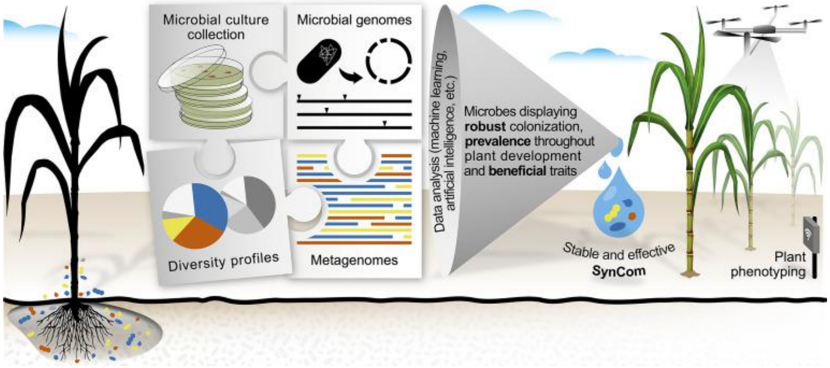

Figure 2 A framework for tailoring stable and effective synthetic microbial communities (SynComs) to enhance crop resiliency to environmental stresses (Adopted from Souza et al., 2020)

Image caption: The selection of microbes in a culture collection is based on functional and empirical evidence, regardless of taxonomic classification. The rationale is driven by using both genome and microbial profiling data in the selection of key microbial candidates. Machine learning and artificial intelligence computational tools drive crucial steps in identifying microorganisms possessing traits for robust colonization, prevalence throughout plant development, and specific beneficial functions for plants. As a proof of concept for SynCom effectiveness, tools for plant phenotyping serve as an important diagnostic platform for measuring the impact of SynComs addressing the demand for both increased productivity and plant resiliency (Adopted from Souza et al., 2020)

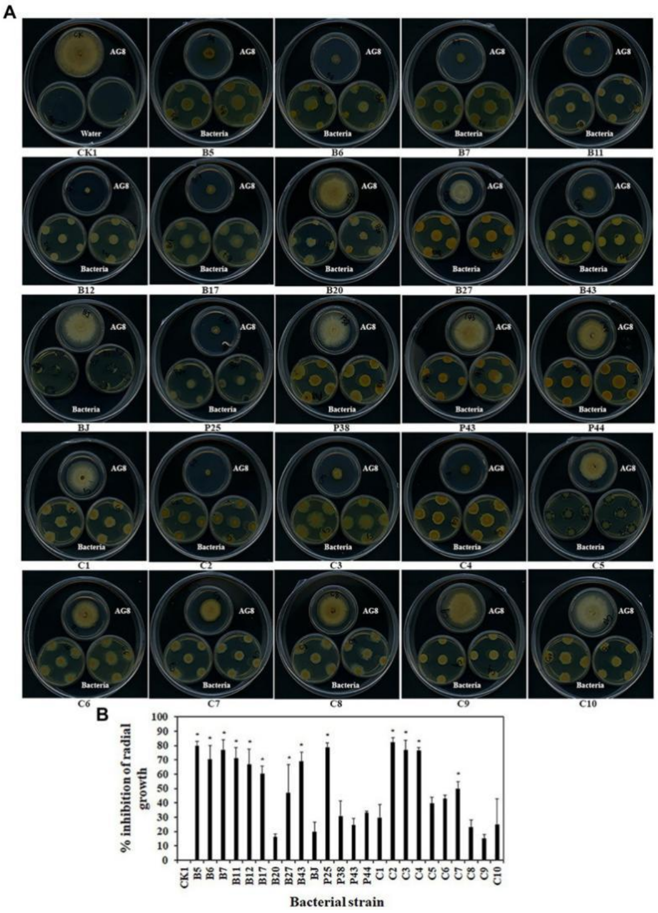

Figure 3 Effects of bacterial volatiles on the growth of *R. solani* AG8 (Adopted from Yin et al., 2022)

Image caption: (A). The growth of AG8. (B). Inhibition of radial growth of AG8. CK1: ddH_2O; B5: *Pseudomonas* sp. B5; B6: *Streptomyces* sp. B6; B7: *Chryseobacterium* sp. B7; B11: *Pseudomonas* sp. B11; B12: *Pseudomonas* sp. B12; B17: *Sphingomonas* sp. B17; B20: *Cupriavidus campinensis* B20; B27: *Asticcacaulis* sp. B27; B43: *Rhodococcus erythropolis* B43; BJ: *Janthinobacterium lividum* BJ; P25: *Pseudomonas* sp. P25; P38: *Chryseobacterium soldanellicola* P38; P43: *Chryseobacterium* sp. P43; P44: *Pedobacter* sp. P44; C1: SynCom 1; C2: SynCom 2; C3: SynCom 3; C4: SynCom 4; C5: SynCom 5; C6: SynCom 6; C7: SynCom 7; C8: SynCom 8; C9: SynCom 9; C10: SynCom 10. The values are means ± SD. Asterisks indicate significant differences ($p \leqslant 0.05$, Dunn test, $n = 3$) (Adopted from Yin et al., 2022)

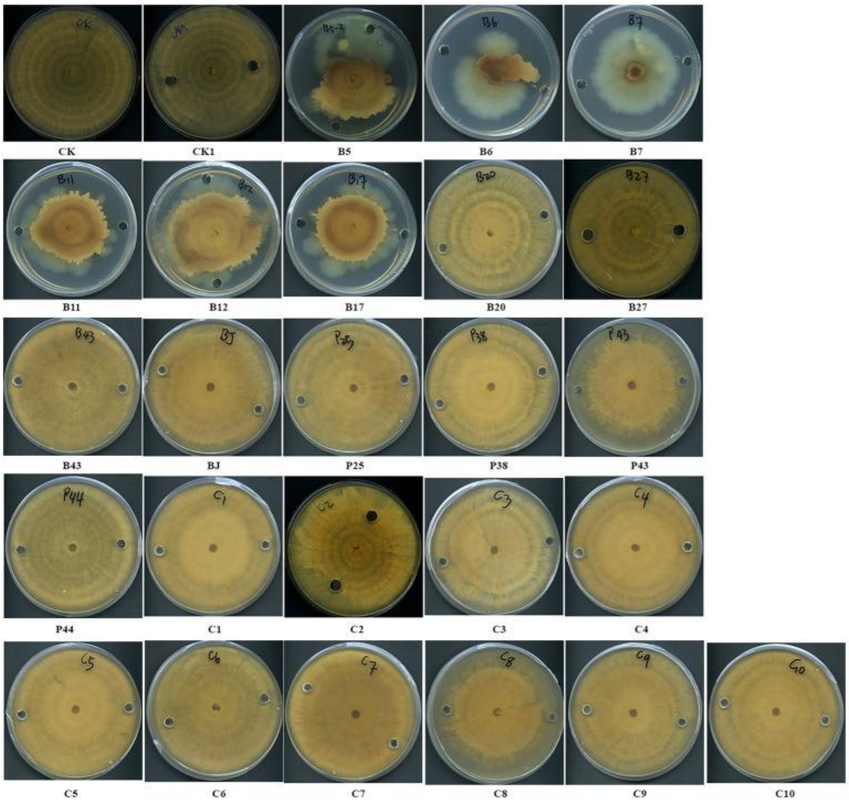

Figure 4 Effects of cell-free supernatants (CFSs) of bacteria on the growth of *R. solani* AG8 (Adopted from Yin et al., 2022)
Image caption: CK: AG8 only; CK1: ddH_2O; B5: CFSs of *Pseudomonas* sp. B5; B6: CFSs of *Streptomyces* sp. B6; B7: CFSs of *Chryseobacterium* sp. B7; B11: CFSs of *Pseudomonas* sp. B11; B12: CFSs of *Pseudomonas* sp. B12; B17: CFSs of *Sphingomonas* sp. B17; B20: CFSs of *Cupriavidus campinensis* B20; B27: CFSs of *Asticcacaulis* sp. B27; B43: CFSs of *Rhodococcus erythropolis* B43; BJ: CFSs of *Janthinobacterium lividum* BJ; P25: CFSs of *Pseudomonas* sp. P25; P38: CFSs of *Chryseobacterium soldanellicola* P38; P43: CFSs of *Chryseobacterium* sp. P43; P44: CFSs of *Pedobacter* sp. P44; C1: CFSs of SynCom 1; C2: CFSs of SynCom 2; C3: CFSs of SynCom 3; C4: CFSs of SynCom 4; C5: CFSs of SynCom 5; C6: CFSs of SynCom 6; C7: CFSs of SynCom 7; C8: CFSs of SynCom 8; C9: CFSs of SynCom 9; C10: CFSs of SynCom 10 (Adopted from Yin et al., 2022)

6.3 Limitations and areas for improvement

Despite the promising outcomes, there are several limitations and areas for improvement in the application of SynComs for climate-resilient agriculture. One major limitation is that SynComs were not more effective than single strains in some cases, such as in the reduction of wheat root rot disease (Yin et al., 2022). This suggests that further research is needed to understand the interactions between different microbial strains and their collective impact on plant health. Additionally, while computational methods have advanced the design of SynComs, there is still a need for more robust and comprehensive models that can accurately predict the best microbial combinations for various crops and environmental conditions (Souza et al., 2020). Future research should focus on refining these models and exploring the synergistic effects of different microbial strains to enhance the overall efficacy of SynComs in field applications.

7 Challenges and Limitations

7.1 Technical challenges in engineering and deploying SynComs

Engineering and deploying synthetic microbial communities (SynComs) for agricultural applications face several technical challenges. One significant issue is the reproducibility of SynComs in different field conditions. The performance of SynComs can vary widely due to differences in crops, soil types, and environmental conditions, which complicates their consistent application (Sai et al., 2022; Shayanthan et al., 2022).

Additionally, the complexity of designing stable and effective SynComs that can robustly colonize and persist in the plant microbiome is a major hurdle (Song et al., 2024). Computational methods, including machine learning and artificial intelligence, are being leveraged to screen and identify beneficial microbes, but these approaches are still in their infancy and require further refinement (Souza et al., 2020). Moreover, the interaction dynamics between SynCom members and the host plant, as well as among the microbial members themselves, add another layer of complexity that needs to be understood and managed (Yin et al., 2022).

7.2 Ecological and environmental considerations

The introduction of SynComs into agricultural ecosystems raises several ecological and environmental concerns. One primary concern is the potential impact on native microbial communities and the broader ecosystem. The introduction of non-native microbial strains could disrupt existing microbial networks and ecological balances, leading to unintended consequences (Pradhan et al., 2022). Additionally, the long-term ecological impacts of SynComs are not well understood, and there is a risk that these engineered communities could outcompete or displace native beneficial microbes, potentially leading to reduced biodiversity (Arnault et al., 2023). Furthermore, the environmental conditions, such as soil type and climate, can significantly influence the effectiveness and stability of SynComs, making it challenging to predict their performance across different agricultural settings (Sai et al., 2022).

7.3 Economic and scalability issues

The economic viability and scalability of SynComs are critical factors that need to be addressed for their widespread adoption. Developing and producing SynComs at a commercial scale can be cost-prohibitive, particularly given the need for precise formulation and quality control (Shayanthan et al., 2022). Additionally, the variability in field performance necessitates extensive field trials and optimization, which can be resource-intensive and time-consuming (Yin et al., 2022). The scalability of SynComs also depends on the ability to produce them in large quantities while maintaining their functional integrity and effectiveness. This requires advancements in biotechnological processes and infrastructure to support large-scale production and distribution (Sai et al., 2022).

7.4 Regulatory and safety concerns

The deployment of SynComs in agriculture is subject to regulatory scrutiny and safety concerns. Regulatory frameworks for the use of genetically engineered microorganisms in agriculture are still evolving, and there is a need for clear guidelines and standards to ensure the safe use of SynComs (Pradhan et al., 2022). Safety concerns include the potential for horizontal gene transfer between SynCom members and native microbes, which could lead to the spread of undesirable traits (Shayanthan et al., 2022). Additionally, there is a need to assess the potential risks to human health and the environment, including the possibility of SynComs affecting non-target organisms or entering the food chain (Arnault et al., 2023). Addressing these regulatory and safety concerns is essential to gain public trust and ensure the responsible use of SynComs in agriculture.

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 enhance their application in agriculture. One significant trend is the integration of computational methods, such as machine learning and artificial intelligence, to screen and identify beneficial microbes, thereby improving the process of determining the best combination of microbes for desired plant phenotypes (Souza et al., 2020). Additionally, advances in omics technologies, including genomics, proteomics, and metabolomics, are being leveraged to gain deeper insights into plant-microbe interactions and to design more effective SynComs (Pradhan et al., 2022). The use of non-invasive real-time phenotyping platforms to monitor plant physiological responses to SynCom inoculation is another promising development, allowing for the precise measurement of temporal variations in plant traits under different environmental conditions (Armanhi et al., 2021). Furthermore, remote sensing technologies are being employed to assess crop status at field scale, integrating big data into predictive and prescriptive management tools to enhance agricultural resilience (Jung et al., 2020).

8.2 Integration of SynComs into broader agricultural practices

Integrating SynComs into broader agricultural practices involves several strategies aimed at enhancing crop resilience and sustainability. One approach is the use of SynComs to improve plant health and productivity by modulating the plant microbiota, as demonstrated by successful seedling microbiota engineering using SynCom inoculation on seeds (Arnault et al., 2023). This method has shown promise in outcompeting native microbiota and effectively colonizing seedlings, thereby enhancing plant fitness. Additionally, SynComs have been used to protect crops against soilborne pathogens, such as the protection of wheat from Rhizoctonia solani infection (Yin et al., 2022). The potential of SynComs to mitigate biotic stresses through rhizosphere engineering and the integration of traditional and modern techniques is also being explored (Pradhan et al., 2022). Moreover, the resilience of integrated agricultural systems (IAS) to climate variability and change has been highlighted, suggesting that farm system integration can enhance resilience, although further research is needed to test the effectiveness of integration policies (Gil et al., 2017).

8.3 Potential breakthroughs and long-term vision for climate-resilient agriculture

The long-term vision for climate-resilient agriculture involves several potential breakthroughs that could transform agricultural practices. One such breakthrough is the development of SynComs tailored to enhance crop resilience against both biotic and abiotic stresses, thereby reducing dependency on chemical fertilizers and improving crop performance on marginal soils (Sai et al., 2022). The use of genetic strategies to improve crop yields and resilience in the face of climatic stress is another promising avenue, leveraging naturally evolved traits and transformative engineering to create resilient production systems (Bailey-Serres et al., 2019). Agroecological strategies, such as diversification of agroecosystems and the integration of traditional farming principles, are also being considered to enhance the resilience of agricultural systems to climatic extremes (Altieri et al., 2015). The effective diffusion of agroecological technologies and the scaling up of practices that enhance agroecosystem resilience will be crucial in adapting to climate change and ensuring food security in the future.

By harnessing these emerging trends, integrating SynComs into broader agricultural practices, and pursuing potential breakthroughs, the vision of climate-resilient agriculture can be realized, ensuring sustainable food production in the face of global environmental challenges.

9 Concluding Remarks

The field trials and performance evaluations of engineered synthetic microbial communities (SynComs) have demonstrated significant potential in enhancing crop resiliency under adverse environmental conditions. The integration of microbial ecology and genetics in designing SynComs has shown promising results in delivering stable and effective inoculants tailored for robust colonization and specific beneficial functions for plants. Additionally, the use of computational methods, including machine learning and artificial intelligence, has improved the screening and identification of beneficial microbes, thereby optimizing the combination of microbes for desired plant phenotypes. Furthermore, the socio-ecological extension system (SEES) has proven effective in promoting climate-resilient agriculture by facilitating technology adaptations among rice farmers, as evidenced by higher Technology Adaptation Index (TAI) scores compared to conventional methods.

For policymakers, the findings underscore the importance of supporting research and development in microbial inoculants and SynComs to enhance agricultural resilience. Policies that promote the integration of advanced computational methods in agricultural practices can further optimize crop performance under climate stress. Researchers are encouraged to continue exploring the interactions between plants and microbial communities to identify novel beneficial traits and improve the design of SynComs. The success of SEES in promoting technology adaptation among farmers highlights the need for participatory and flexible extension approaches that integrate natural and social processes with technological innovations. Farmers can benefit from adopting SynComs and SEES frameworks to improve crop resilience and productivity in the face of climate challenges.

The promising results from the field trials of SynComs and the SEES approach call for further research and collaboration among scientists, policymakers, and farmers. Future studies should focus on long-term field trials to assess the sustainability and scalability of SynComs in diverse agro-ecosystems. Collaborative efforts are needed to refine computational methods for better screening and combination of beneficial microbes. Additionally, expanding the SEES framework to other regions and crops can provide valuable insights into its broader applicability and effectiveness. By fostering interdisciplinary collaboration and continuous innovation, we can advance the development of climate-resilient agricultural practices that ensure food security and environmental sustainability.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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