Research Report Open Access

Optimizing Engineered SynComs for Controlled Environment Agriculture (CEA): From Theory to Commercialization

Dandan Huang

Hainan Institute of Biotechnology, Haikou, 570206, Hainan, China

Corresponding email: 3196820059@qq.com

International Journal of Horticulture, 2024, Vol.14, No.3 doi: 10.5376/ijh.2024.14.0022

Received: 10 Apr., 2024

Accepted: 25 Jun., 2024

Published: 03 Jul., 2024

Preferred citation for this article:

Huang D.D., 2024, Optimizing engineered SynComs for controlled environment agriculture (CEA): from theory to commercialization, International Journal of Horticulture, 14(3): 195-206 (doi: 10.5376/ijh.2024.14.0022)

Abstract This study synthesizes research findings on the use of Digital Twin architectures, machine learning models, genetic engineering, and automated control systems to optimize SynComs for CEA. Key findings include the effective use of Digital Twin and reinforcement learning models to improve crop management, the importance of breeding and genetic engineering in developing crops suited for controlled environments, and the deployment of advanced automation systems to enhance precision in environmental control. This study also highlights the significant improvements in energy efficiency through technological advancements in lighting and climate control. The implications of these findings for researchers, policymakers, and industry stakeholders are discussed, emphasizing the need for interdisciplinary collaboration and continued research to fully realize the potential of SynComs in CEA. This study calls for supportive policies, investment in state-of-the-art technologies, and collaborative efforts to drive innovation and sustainability in controlled environment agriculture.

Keywords Synthetic microbial communities (SynComs); Controlled environment agriculture (CEA); Genetic engineering; Automated control systems; Energy efficiency

Introduction

Controlled Environment Agriculture (CEA) represents a revolutionary approach to agricultural production, characterized by its ability to optimize resource use, minimize spatial requirements, and significantly enhance yield outputs. By leveraging advanced technologies, CEA systems create ideal growing conditions for crops, irrespective of external environmental factors. This method encompasses various setups, including greenhouses, vertical farms, and plant factories, each designed to maintain precise control over environmental parameters such as temperature, humidity, light, and nutrient supply (Ojo and Zahid, 2022).

Engineered synthetic microbial communities (SynComs) have emerged as a pivotal innovation within CEA, offering substantial benefits in terms of plant health, growth, and productivity. SynComs are meticulously designed consortia of microorganisms that interact synergistically to promote plant growth, enhance nutrient uptake, and protect against pathogens. The integration of SynComs into CEA systems can lead to more resilient and efficient agricultural practices, ultimately contributing to sustainable food production (Amitrano et al., 2020).

The objective of this study is to provide a comprehensive analysis of the current state of optimizing engineered SynComs for Controlled Environment Agriculture (CEA). By synthesizing findings from multiple studies, this study aims to identify key trends, challenges, and opportunities in the field, offering a forward-looking perspective on the commercialization potential of SynComs in CEA. It will delve into the theoretical foundations of SynComs, evaluate their practical applications, and propose strategies to overcome existing commercialization barriers. This study is significant for guiding future research, informing policy decisions, and fostering innovation in sustainable agriculture, ultimately contributing to the achievement of efficient agricultural systems through advanced biotechnological solutions.

1 Theoretical Foundations of Engineered SynComs

1.1 Definition and principles of SynComs

Synthetic microbial communities (SynComs) are carefully designed consortia of microorganisms that are assembled to perform specific functions beneficial to plant health and productivity. These communities are not randomly assembled but are structured based on ecological theories and principles to ensure stability and functionality under various environmental conditions (Shayanthan et al., 2022; Martins et al., 2023). SynComs aim to mimic natural microbial communities by incorporating multiple taxa that can interact synergistically to enhance plant growth, nutrient acquisition, and stress resilience (Souza et al., 2020; Sai et al., 2022).

1.2 Mechanisms of microbial interactions in SynComs

Microbial interactions within SynComs are complex and multifaceted, involving various mechanisms such as competition, mutualism, and commensalism. These interactions can influence the overall stability and functionality of the SynCom. For instance, microbial biofilm formation, production of secondary metabolites, and induction of plant resistance are critical traits that contribute to the effectiveness of SynComs (Martins et al., 2023). Additionally, microbial interactions can modulate plant signaling networks, such as nitrogen and phosphorus pathways, which are crucial for nutrient acquisition and growth (Wang et al., 2021). Understanding these interactions is essential for designing SynComs that can consistently perform under different environmental conditions (Pradhan et al., 2022; Fonseca-García et al., 2023).

1.3 Genetic and synthetic biology approaches for engineering SynComs

Advances in genetic and synthetic biology have significantly contributed to the development of SynComs. Techniques such as next-generation sequencing (NGS) and machine learning are employed to identify and select microbial strains with desirable traits (Shayanthan et al., 2022; Wang et al., 2023). Genetic engineering allows for the modification of microbial genomes to enhance specific functions, such as nutrient solubilization or stress tolerance. Synthetic biology approaches enable the construction of microbial consortia with defined compositions and functions, ensuring that the SynCom can perform reliably in controlled environment agriculture (CEA) settings (Souza et al., 2020; Armanhi et al., 2021). These approaches also facilitate the study of microbial community dynamics and the development of strategies to maintain SynCom stability and functionality over time (Sai et al., 2022).

By integrating ecological principles, microbial interactions, and advanced genetic tools, the theoretical foundations of engineered SynComs provide a robust framework for optimizing their application in CEA. This study aims to explore these foundations in detail, highlighting the potential and challenges of SynComs from theory to commercialization.

2 SynComs in Controlled Environment Agriculture

2.1 Role of SynComs in enhancing plant growth and health in CEA

Synthetic microbial communities (SynComs) play a crucial role in enhancing plant growth and health within controlled environment agriculture (CEA) systems. SynComs are engineered consortia of microbes designed to produce specific beneficial functions for plants, such as promoting growth, improving nutrient acquisition, and enhancing resistance to environmental stressors. These communities are not randomly assembled; instead, they are structured based on ecological theories and machine learning insights to ensure stability and effectiveness (Souza et al., 2020; Marín et al., 2021; Martins et al., 2023). For instance, SynComs have been shown to significantly improve plant health by forming biofilms, producing secondary metabolites, and inducing plant resistance mechanisms (Martins et al., 2023). Additionally, SynComs can be tailored to thrive under specific environmental conditions, making them particularly suitable for the controlled settings of CEA (Marín et al., 2021).

2.2 Examples of SynCom applications in hydroponics, aquaponics, and vertical farming

SynComs have been successfully applied in various CEA systems, including hydroponics, aquaponics, and vertical farming (Figure 1). In hydroponic systems, SynComs have been used to enhance nutrient uptake and plant growth. For example, a study demonstrated that SynComs constructed from root-associated microbes significantly promoted soybean growth and nutrient acquisition, leading to increased yields (Wang et al., 2021). In aquaponics, SynComs can be integrated with recirculating aquaculture systems (RAS) to repurpose nutrient-dense effluents as naturally derived nutrient solutions for hydroponic vegetable production, thereby creating a circular bioeconomy (Tetreault et al., 2023). Vertical farming, which often relies on LED lighting and precise environmental controls, can also benefit from SynComs. These microbial communities can be designed to optimize plant health and productivity under the unique conditions of vertical farms (Niu and Masabni, 2018; Alrajhi et al., 2023).

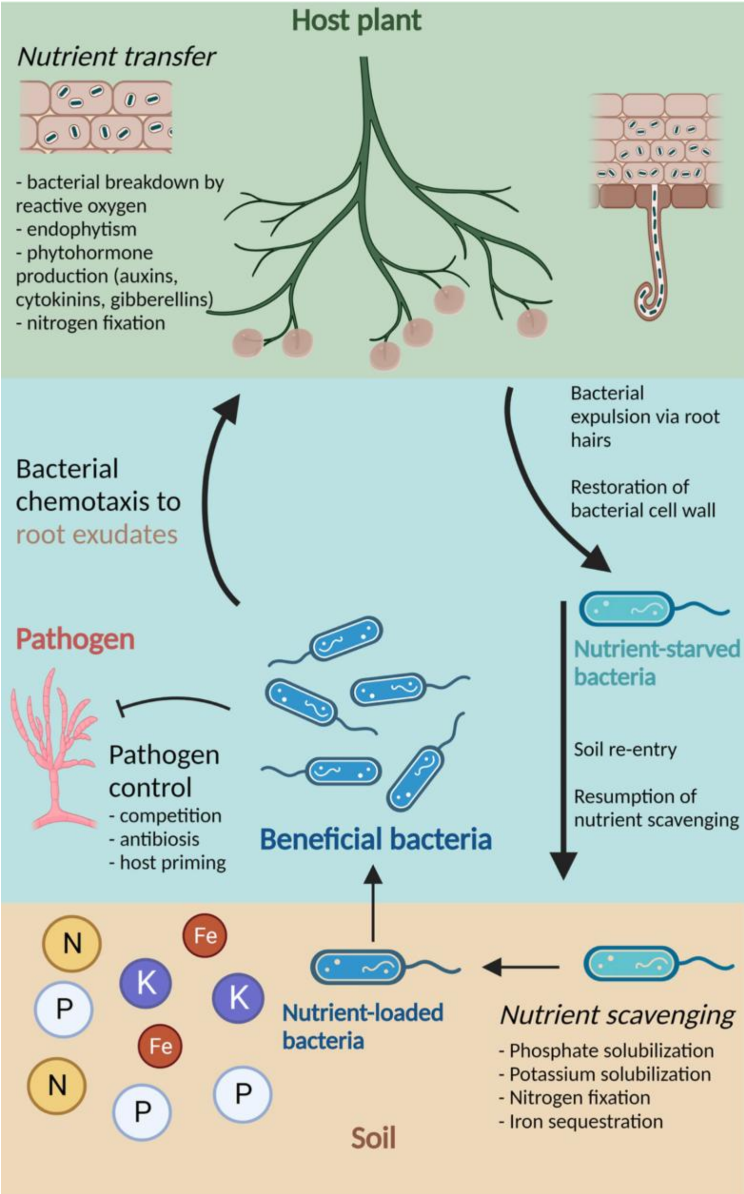

Figure 1 Schematic representation of the growth-promotional and defensive functions provided by beneficial bacteria, including participation in the rhizophagy cycle (Adopted from Chiaranunt and White, 2023)

Image caption: The host plant (labeled in green) breaks down soil bacteria with ROS, allowing for endophytism and transfer of nutrients and phytohormones; Following this, nutrient-starved bacteria are expelled via root hairs, where they can restore their cell walls; In soil, bacteria resume nutrient scavenging, which includes phosphate and potassium solubilization, nitrogen fixation, and iron sequestration; Nutrient-loaded bacteria (labeled in blue) are subsequently attracted back to the host plant via root exudates, where they are degraded by ROS and nutrient transfer can occur again; Throughout this cycle, beneficial bacteria may also participate in pathogen control through competition, antibiosis, and priming of the host plant’s resistance (Adopted from Chiaranunt and White, 2023)

2.3 Comparative analysis of SynComs versus traditional microbial inoculants

When comparing SynComs to traditional microbial inoculants, several advantages become apparent. Traditional inoculants typically consist of single or a few microbial strains selected for specific beneficial traits. However, these inoculants often fail to establish stable and effective microbial communities in the plant rhizosphere, leading to inconsistent results (Souza et al., 2020; Martins et al., 2023). In contrast, SynComs are designed using a more holistic approach that considers the complex interactions between multiple microbial species, plants, and the environment. This results in more stable and resilient microbial communities that can better withstand environmental stressors and provide consistent benefits to plants (Souza et al., 2020; Marín et al., 2021; Martins et al., 2023). Additionally, SynComs can be tailored to target specific plant phenotypes and functions, making them more versatile and effective than traditional inoculants (Souza et al., 2020; Martins et al., 2023). For instance, SynComs have been shown to regulate nutrient signaling networks at the transcriptional level, leading to enhanced growth pathways and improved plant performance (Wang et al., 2021).

In summary, SynComs offer a promising alternative to traditional microbial inoculants in CEA by providing more stable, resilient, and effective microbial communities that enhance plant growth and health. Their applications in hydroponics, aquaponics, and vertical farming demonstrate their versatility and potential to revolutionize plant production in controlled environments.

3 Optimization Strategies for SynComs in CEA

3.1 Selection and engineering of microbial strains for specific agricultural goals

The selection and engineering of microbial strains are critical for optimizing synthetic microbial communities (SynComs) in controlled environment agriculture (CEA). The primary goal is to identify and utilize microbial strains that can enhance plant health, growth, and resilience. This involves selecting microbes with beneficial traits such as biofilm formation, production of secondary metabolites, and the ability to induce plant resistance (Martins et al., 2023). Additionally, computational methods, including machine learning and artificial intelligence, can be employed to screen and identify beneficial microbes, ensuring the best combination of strains for desired plant phenotypes (Souza et al., 2020). The use of functional screening to construct SynComs has shown promising results in improving nutrient acquisition and crop yield, as demonstrated in soybean plants (Wang et al., 2021).

3.2 Optimization of SynCom composition and diversity

Optimizing the composition and diversity of SynComs is essential for their stability and effectiveness in CEA systems. Studies have shown that well-structured microbial assemblages are more likely to thrive under environmental stressors compared to single microbial activities or taxonomies (Martins et al., 2023). The diversity of SynComs can be maintained by adjusting the starting composition ratios and using low-nutrient media to support the growth of individual organisms (Coker et al., 2022). Additionally, the use of model synthetic communities, such as those developed for the rhizosphere, can provide reproducible and stable systems for research and application in CEA (Coker et al., 2022). The functional assembly of root-associated microbial consortia has also been shown to improve nutrient efficiency and yield in crops like soybean (Wang et al., 2021).

3.3 Techniques for monitoring and managing SynComs in CEA systems

Effective monitoring and management of SynComs in CEA systems are crucial for their success. Proximal sensors and non-destructive technologies can be used to monitor plant growth, yield, and water consumption, providing real-time data for managing SynComs (Amitrano et al., 2020). Deep learning (DL) methods have also been applied to CEA for crop monitoring, detecting biotic and abiotic stresses, and predicting crop growth (Ojo and Zahid, 2022). Additionally, digital twin (DT) architectures can optimize productivity by simulating and controlling crop microclimates and management strategies (Chaux et al., 2021). Proper water management is another critical factor, as it influences the availability of nutrients, plant physiological processes, and microbial communities within the rhizosphere (Tan et al., 2021). By integrating these advanced monitoring and management techniques, CEA systems can achieve better yields and quality crops while maintaining the stability and effectiveness of SynComs.

4 Performance Evaluation of Engineered SynComs

4.1 Criteria and metrics for assessing SynCom performance

The performance of engineered synthetic microbial communities (SynComs) in controlled environment agriculture (CEA) can be evaluated using several criteria and metrics. Key performance indicators include crop yield, disease resistance, nutrient acquisition, and overall plant health. For instance, the application of SynComs has been shown to significantly enhance nutrient efficiency and crop yield in soybean, with yield increases of up to 36.1% observed in field trials (Wang et al., 2021). Additionally, the ability of SynComs to promote plant growth under nutrient-deficient conditions is a critical metric, as demonstrated by the improved nutrient acquisition and growth in soybean plants (Wang et al., 2021). Other important metrics include the stability and prevalence of beneficial microbial traits throughout plant development, which are essential for ensuring the long-term effectiveness of SynComs (Souza et al., 2020).

4.2 Case studies of SynCom implementation in CEA

Several case studies highlight the successful implementation of SynComs in CEA systems. For example, a study on the functional assembly of root-associated microbial consortia in soybean demonstrated significant improvements in plant growth and nutrient acquisition under both nutrient-deficient and sufficient conditions (Wang et al., 2021). This study underscores the potential of SynComs to enhance crop performance in controlled environments. Another case study focused on the design of SynComs for improved crop resiliency, emphasizing the importance of selecting microbial strains with robust colonization abilities and specific beneficial functions for plants (Souza et al., 2020). These case studies illustrate the practical applications of SynComs in enhancing crop productivity and resilience in CEA systems.

4.3 Analysis of factors influencing SynCom effectiveness in controlled environments

The effectiveness of SynComs in controlled environments is influenced by several factors, including the composition of the microbial community, environmental conditions, and the specific crop being cultivated. The selection of microbial strains with beneficial traits, such as nutrient acquisition and disease resistance, is crucial for the success of SynComs (Souza et al., 2020). Additionally, environmental factors such as light spectra, temperature, and humidity can impact the performance of SynComs. For instance, the use of different LED light spectra has been shown to affect the growth, yield, and nutritional value of lettuce in CEA systems (Alrajhi et al., 2023). Furthermore, the integration of advanced technologies, such as digital twin architectures, can optimize the productivity of CEA systems by simulating and controlling crop microclimate and management strategies (Chaux et al., 2021). Overall, a comprehensive understanding of these factors is essential for optimizing the performance of SynComs in controlled environments.

5 From Laboratory to Field: Scaling Up SynComs

5.1 Challenges in scaling up SynComs from laboratory to commercial CEA systems

Scaling up synthetic microbial communities (SynComs) from laboratory settings to commercial controlled environment agriculture (CEA) systems presents several challenges. One of the primary issues is the complexity of maintaining the stability and functionality of SynComs in diverse and dynamic field conditions. Laboratory conditions are highly controlled, whereas commercial CEA systems are subject to variations in environmental factors such as temperature, humidity, and light, which can affect microbial community dynamics and plant-microbe interactions (Wang et al., 2021; Pradhan et al., 2022). Additionally, the economic feasibility of producing and applying SynComs at a large scale is a significant hurdle. The cost of isolating, screening, and maintaining beneficial microbial strains can be prohibitive, and there is a need for cost-effective production methods that can be scaled up without compromising the efficacy of the SynComs (Wang et al., 2021; Pradhan et al., 2022). Furthermore, regulatory and safety concerns must be addressed to ensure that the introduction of SynComs into commercial agriculture does not pose risks to human health or the environment (Pradhan et al., 2022).

5.2 Strategies for large-scale production and deployment of SynComs

To overcome the challenges associated with scaling up SynComs, several strategies can be employed. One approach is the development of robust production systems that can generate large quantities of microbial inoculants efficiently. This includes optimizing fermentation processes and developing formulations that enhance the shelf-life and stability of SynComs under various storage and application conditions (Wang et al., 2021). Another strategy involves the use of advanced biotechnological tools, such as omics technologies and machine learning, to design and optimize SynComs for specific crops and environmental conditions (Figure 2) (Pradhan et al., 2022). These tools can help identify key microbial traits and interactions that are critical for enhancing plant growth and resilience, thereby enabling the creation of more effective SynComs. Additionally, integrating SynComs with other sustainable agricultural practices, such as precision agriculture and digital twin technologies, can enhance their deployment and monitoring in commercial CEA systems (Chaux et al., 2021; Ojo and Zahid, 2022). This integration can facilitate real-time adjustments to environmental conditions and microbial applications, ensuring optimal performance of SynComs in the field.

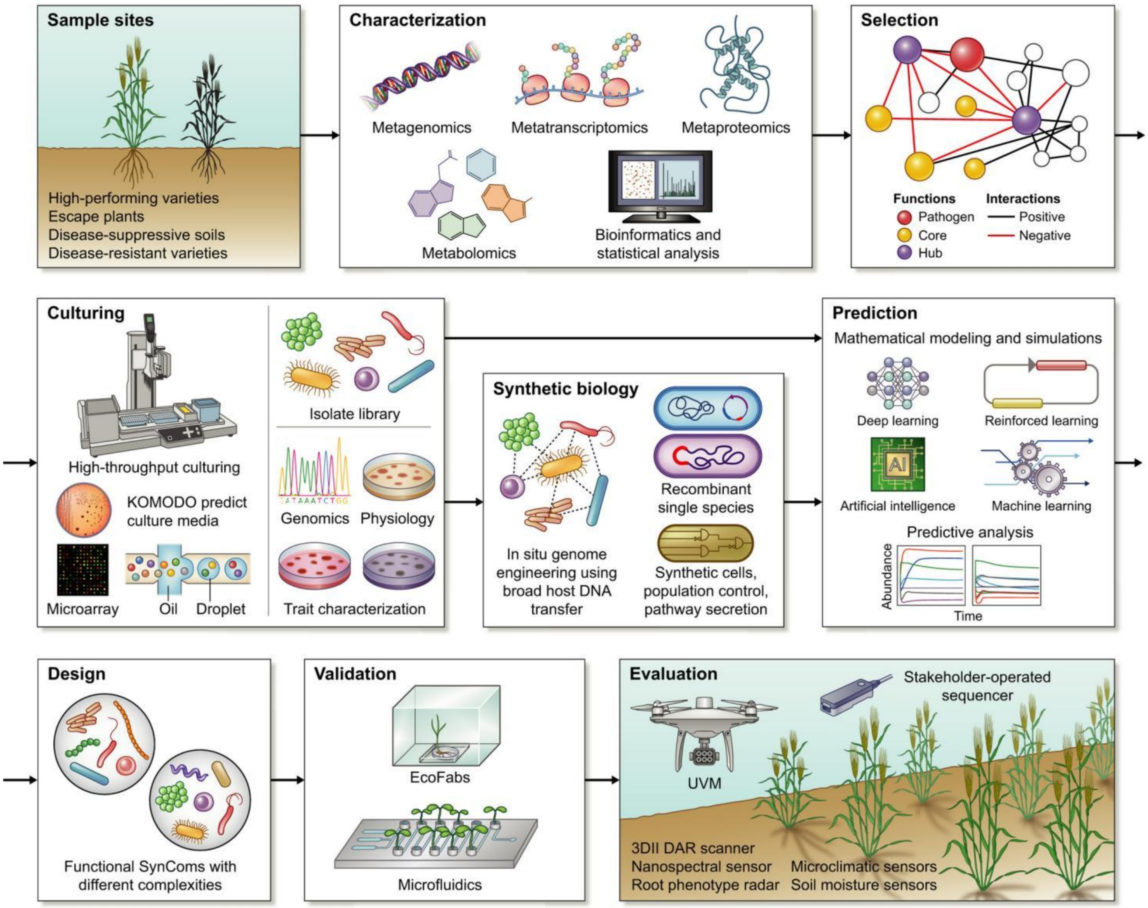

Figure 2 Proposed technical flow for artificial construction of a synthetic microbial community (SynCom) to augment plant fitness and productivity (Adopted from Trivedi et al., 2021)

Image caption: Microbiomes from sites with disease suppression or better plant performance are characterized using multiomics techniques; The beneficial microbiome is selected through construction of an interaction network and potential key microbes are identified based on structural properties and/or functional modules; Individual microbial members are cultured using high-throughput platforms and characterized through genomic, metabolic and physiological analysis; The isolates are screened first for beneficial traits and then in binary microbe-microbe and in plant-microbiome interactions using microfluidics-based platforms; Desirable functions for microbes destined for inclusion in SynComs may be improved through synthetic biology; SynComs with different complexities are designed through predictive modeling that evaluates trait redundancy, dominance, modularity, interactions and assembly; SynComs are further validated for their plant growth promotion abilities in the glasshouse or using standardized fabricated ecosystems or microfluidic platforms for reproducible interrogation of beneficial traits; The most promising SynComs are applied to fields where a variety of sensors mounted on unmanned aerial vehicles coupled with mobile DNA sequencers will allow automated monitoring of the plant response and microbial community structures; Integration of microbiome-phenome-environment datasets will be used to forecast microbial dynamics and enable scaleup of SynCom application in smart farming systems (Adopted from Trivedi et al., 2021)

5.3 Case studies of successful commercialization efforts

Several case studies highlight the successful commercialization of SynComs in CEA systems. For instance, a study on the application of root-associated SynComs in soybean demonstrated significant improvements in nutrient acquisition and yield under both nutrient-deficient and sufficient conditions. Field trials revealed that the application of SynComs led to yield increases of up to 36.1%, showcasing the potential of these microbial communities to enhance crop productivity in commercial settings (Wang et al., 2021) (Figure 3). Another example is the use of digital twin architectures in CEA systems to optimize productivity and resource use. By simulating crop growth and environmental conditions, digital twins can help fine-tune the application of SynComs, ensuring that they perform effectively under varying conditions (Chaux et al., 2021). These case studies underscore the importance of integrating advanced technologies and robust production methods to achieve successful commercialization of SynComs in CEA systems.

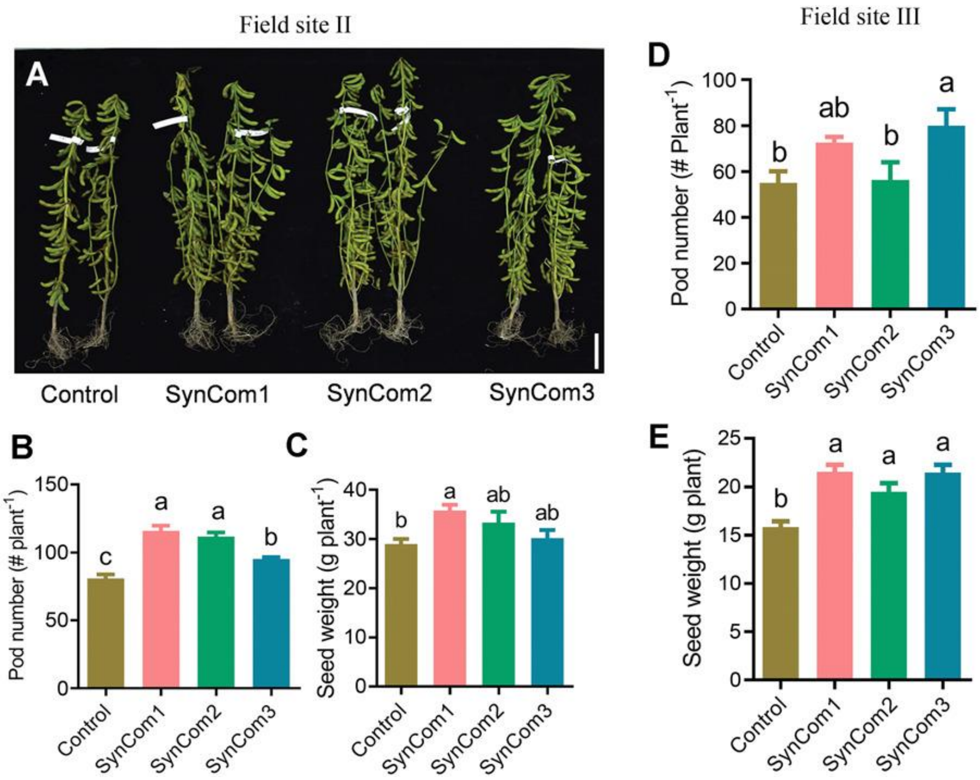

Figure 3 Field application of SynComs in different sites (Adopted from Wang et al., 2021)

Image caption: (A) Yield performance, bar = 10 cm; (B, D) Pod number; (C, E) Seed weight; Soybean plants with or without SynCom application were grown in field site II (A-C) and III (D, E); Different letters indicate significant differences among different treatments in Duncan's multiple comparisons test; Among the three SynComs, SynCom1 exhibited the highest and most stable promotion effects on soybean yield, as reflected by increases of 43.4% and 32.1% in pod number, and 23.3% and 36.1% in seed weight at site II and site III, respectively, in comparison with uninoculated control plants (Adopted from Wang et al., 2021)

6 Regulatory and Safety Considerations

6.1 Regulatory frameworks governing the use of SynComs in agriculture

The use of synthetic microbial communities (SynComs) in agriculture is subject to various regulatory frameworks that ensure their safe and effective application. Regulatory bodies such as the Environmental Protection Agency (EPA) in the United States and the European Food Safety Authority (EFSA) in Europe have established guidelines for the approval and monitoring of microbial inoculants. These frameworks typically require comprehensive risk assessments, including the evaluation of potential environmental impacts and human health risks associated with the release of SynComs into agricultural settings (Dsouza et al., 2021; Martins et al., 2023). Additionally, international standards such as those set by the International Organization for Standardization (ISO) provide guidelines for the safe handling and application of microbial products in agriculture (Martins et al., 2023).

6.2 Safety and risk assessment protocols for SynComs

Safety and risk assessment protocols for SynComs involve a multi-faceted approach to ensure that these microbial communities do not pose any harm to plants, animals, humans, or the environment. Key components of these protocols include microbial characterization, ecological impact assessment, toxicological studies and field trials. Researchers identify and characterize in detail the microbial strains used in SynComs, including their genetic makeup, metabolic capabilities, and pathogenicity potential (Souza et al., 2020; Martins et al., 2023); evaluate the potential impacts of SynComs on native microbial communities and overall ecosystem health, which includes studying the potential for horizontal gene transfer and the stability of microbial populations over time (Dsouza et al., 2021; Martins et al., 2023); conduct toxicological assessments to identify any adverse effects on non-target organisms, including beneficial insects, soil animals, and humans (Souza et al., 2020; Martins et al., 2023); and implement controlled field trials to monitor the performance and safety of SynComs under real agricultural conditions. These trials help in understanding the long-term impacts and efficacy of SynComs in enhancing crop health and yield (Dsouza et al., 2021; Martins et al., 2023).

6.3 Ethical considerations and public perception

The deployment of SynComs in agriculture raises several ethical considerations and public perception issues that need to be addressed to ensure widespread acceptance and responsible use. Ethical considerations include transparency and informed consent, ensuring that farmers and consumers are fully informed about the nature and benefits of SynComs, as well as any potential risks. This involves transparent communication and obtaining informed consent from stakeholders (Gan et al., 2022; Martins et al., 2023); Equity and access, addressing concerns related to the equitable distribution of benefits derived from SynComs, which includes ensuring that smallholder farmers and marginalized communities have access to these technologies and can benefit from their application (Gan et al., 2022; Martins et al., 2023); Environmental justice, considering the potential environmental impacts of SynComs and ensuring that their use does not disproportionately affect vulnerable ecosystems or communities (Gan et al., 2022; Martins et al., 2023). Public perception plays a crucial role in the acceptance and adoption of SynComs in agriculture. Studies have shown that consumer perceptions of new agricultural technologies are influenced by factors such as perceived benefits, safety, and environmental impact (Gan et al., 2022). Therefore, it is essential to engage with the public through education and outreach programs to build trust and address any concerns related to the use of SynComs in agriculture (Gan et al., 2022).

7 Economic Viability and Market Potential

7.1 Cost-benefit analysis of SynCom use in CEA

The economic viability of using synthetic microbial communities (SynComs) in controlled environment agriculture (CEA) is a critical factor for their adoption. Studies have shown that SynComs can significantly enhance plant growth and nutrient acquisition, leading to increased crop yields. For instance, the application of SynComs in soybean cultivation resulted in yield increases of up to 36.1% in field trials, demonstrating their potential to improve economic returns for farmers (Wang et al., 2021). Additionally, the robust optimization of CEA systems under market uncertainty has been shown to improve long-term economic performance, validating the economic viability of multi-mode CEA production (Cetegen and Stuber, 2021). The integration of advanced technologies such as Digital Twins (DT) can further optimize productivity and resource consumption, potentially reducing operational costs and enhancing profitability (Chaux et al., 2021).

7.2 Market trends and potential for SynCom-based products

The market for SynCom-based products in CEA is poised for growth, driven by the increasing demand for sustainable and efficient agricultural practices. The shift towards urban and controlled-environment agriculture is supported by the need to meet food security and environmental sustainability goals (Cowan et al., 2022). The adoption of artificial intelligence and deep learning technologies in CEA, such as computer vision for real-time monitoring and autonomous cultivation, is expected to further drive market expansion (Ojo and Zahid, 2022; Luo et al., 2022). The potential for SynComs to enhance nutrient efficiency and crop yields positions them as valuable inputs in the CEA market, which is increasingly focused on high-tech solutions like indoor vertical farming and hydroponics (Niu and Masabni, 2018).

7.3 Business models for SynCom commercialization

Several business models can be explored for the commercialization of SynComs in CEA. One approach is the direct sale of SynCom products to CEA operators, leveraging the demonstrated benefits of increased yields and nutrient efficiency (Wang et al., 2021). Another model involves the integration of SynComs into comprehensive CEA solutions, including advanced climate control and crop management systems, to offer a bundled package that maximizes productivity and sustainability (Chaux et al., 2021; Lu et al., 2023). Additionally, partnerships with technology providers and agricultural input companies can facilitate the distribution and adoption of SynComs, ensuring that they reach a broader market. The development of subscription-based services for continuous supply and support of SynCom applications could also provide a steady revenue stream while ensuring optimal performance for end-users.

By addressing the economic viability, market potential, and viable business models, the adoption of SynComs in CEA can be effectively strategized to ensure successful commercialization and widespread use.

8 Future Directions and Perspectives

8.1 Emerging technologies and innovations in SynCom engineering

The field of Synthetic Community (SynCom) engineering is rapidly evolving, with several emerging technologies poised to revolutionize Controlled Environment Agriculture (CEA). One significant advancement is the development of Digital Twin (DT) architectures, which enable the simulation and optimization of crop microclimates and management strategies, thereby enhancing productivity and resource efficiency (Chaux et al., 2021). Additionally, the integration of circadian rhythm entrainment using dynamic LED cues has shown promise in improving crop yield and sustainability by synchronizing environmental cues with the natural rhythms of plants (Marie et al., 2022). Advances in bio-automation systems are also noteworthy, as they offer innovative solutions for plant growth in extreme environments, such as space, which could have applications in terrestrial CEA as well (Barreto et al., 2023).

8.2 Integration of SynComs with advanced CEA technologies (e.g., IoT, AI)

The integration of SynComs with advanced CEA technologies, such as the Internet of Things (IoT) and Artificial Intelligence (AI), is a promising direction for future research and development. IoT-enabled sensors and wireless networks can provide real-time monitoring and control of environmental conditions, which is crucial for optimizing plant growth and resource use (Shamshiri et al., 2018). AI and computer vision technologies are being increasingly adopted for autonomous cultivation and harvesting, offering significant improvements in efficiency and productivity (Luo et al., 2022). Furthermore, the use of robust optimization methodologies can enhance the economic viability and resilience of CEA systems under market uncertainties, ensuring long-term sustainability (Cetegen and Stuber, 2021).

8.3 Long-term vision and potential breakthroughs in SynComs for CEA

Looking ahead, the long-term vision for SynComs in CEA includes the development of Integrated System CEA (ISCEA), which aims to deploy multiple CEA systems in a localized and integrated manner to maximize efficiency and minimize environmental impact (Cowan et al., 2022). The transition to urban agriculture and plant factories, supported by advancements in greenhouse automation and energy optimization, represents a significant potential breakthrough (Shamshiri et al., 2018). Additionally, the focus on energy efficiency, particularly through improvements in HVAC, lighting, and distributed generation technologies, is expected to play a critical role in making CEA more sustainable and economically viable (Engler and Krarti, 2021). The continued exploration of temperature effects and the development of decision support tools for optimizing production conditions will further enhance the efficiency and effectiveness of CEA systems (Imler, 2020).

By leveraging these emerging technologies and integrating them with advanced CEA systems, the future of SynComs in controlled environment agriculture looks promising, with the potential to achieve significant breakthroughs in productivity, sustainability, and food security.

9 Concluding Remarks

The optimization of engineered synthetic communities (SynComs) for Controlled Environment Agriculture (CEA) has demonstrated significant potential in enhancing productivity, resource efficiency, and sustainability. Key findings from the literature highlight several critical areas. Firstly, the application of Digital Twin (DT) architectures and reinforcement learning models has proven effective in optimizing climate control and crop management. These technological advancements lead to increased yields and better resource use efficiency, as shown in studies by Chaux et al. (2021) and Lu et al. (2023). Secondly, advances in crop breeding and genetic engineering are crucial. Innovations such as breeding new varieties specifically for controlled environments and employing gene editing technologies are essential for optimizing plant traits to meet the unique demands of CEA. Folta (2018) underscores the importance of these advancements. Thirdly, the deployment of automation and intelligent control systems, including IoT-based monitoring, fuzzy logic controllers, and nanotechnology, has reduced human error and improved precision in environmental controls. This is supported by research from Vishwakarma et al. (2020). Lastly, significant strides have been made in improving the energy efficiency of CEA systems. Advances in LED lighting and climate control technologies are critical for reducing operational costs and minimizing environmental impact, as highlighted by Engler and Krarti (2021).

These findings have several implications for researchers, policymakers, and industry stakeholders. For researchers, there is a clear need for continued interdisciplinary research in optimizing SynComs for CEA. This study should focus on areas such as genetic engineering, automated systems, and machine learning applications. Further studies are necessary to develop and validate new technologies that can be seamlessly integrated into existing CEA frameworks. For policymakers, supportive policies are essential to encourage the adoption of innovative technologies in agriculture. This includes funding for research and development, subsidies for sustainable farming practices, and regulations that facilitate the integration of advanced systems in CEA. For industry stakeholders, investing in state-of-the-art technologies and practices that enhance productivity and sustainability is crucial for commercial viability. This involves embracing automation, optimizing energy use, and adopting genetically engineered crops tailored for controlled environments. Collaboration with research institutions can also drive innovation and improve competitive advantage.

The optimization of engineered SynComs for CEA represents a promising frontier in agricultural science, but it requires a collaborative effort across various disciplines. Engineers, biologists, computer scientists, and agricultural experts must work together to develop integrated solutions that address the complexities of controlled environment farming. Continued research is essential to refine these technologies, improve their scalability, and ensure they meet the evolving needs of the agricultural industry. Only through sustained interdisciplinary collaboration can the full potential of SynComs in CEA be realized, paving the way for a more sustainable and productive agricultural future.

Acknowledgement

Author extends sincere thanks to two anonymous peer reviewers for their invaluable feedback on the manuscript of this study.

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.

References

Alrajhi A., Alsahli A., Alhelal I., Rihan H., Fuller M., Alsadon A., and Ibrahim A., 2023, The effect of LED light spectra on the growth, yield and nutritional value of red and green lettuce (*Lactuca sativa*), Plants, 12(3): 463.
https://doi.org/10.3390/plants12030463
PMid:36771547 PMCid:PMC9919669

Armanhi J., Souza R., Biazotti B., Yassitepe J., and Arruda P., 2021, Modulating drought stress response of maize by a synthetic bacterial community, Frontiers in Microbiology, 12: 747541.
https://doi.org/10.3389/fmicb.2021.747541
PMid:34745050 PMCid:PMC8566980

Amitrano C., Chirico G., Pascale S., Rouphael Y., and Micco V., 2020, Crop management in controlled environment agriculture (CEA) systems using predictive mathematical models, Sensors, 20(11): 3110.
https://doi.org/10.3390/s20113110
PMid:32486394 PMCid:PMC7308940

Barreto R., Cornejo J., Palomares R., Cornejo J., and Vargas M., 2023, controlled environment agriculture and bio-automation systems to improve plant growth methods in space, In 2023 IEEE Seventh Ecuador Technical Chapters Meeting (ECTM), IEEE, pp.1-8.
https://doi.org/10.1109/ETCM58927.2023.10309029
PMid:37821803

Cetegen S., and Stuber M., 2021, Optimal design of controlled environment agricultural systems under market uncertainty, Computers & Chemical Engineering, 149: 107285.
https://doi.org/10.1016/j.compchemeng.2021.107285

Chaux J., Sanchez-Londono D., and Barbieri G., 2021, A digital twin architecture to optimize productivity within controlled environment agriculture, Applied Sciences, 11(19): 8875.
https://doi.org/10.3390/app11198875

Chiaranunt P., and White J. F., 2023, Plant beneficial bacteria and their potential applications in vertical farming systems, Plants, 12(2): 400.
https://doi.org/10.3390/plants12020400
PMid:36679113 PMCid:PMC9861093

Coker J., Zhalnina K., Marotz C., Thiruppathy D., Tjuanta M., D'Elia G., Hailu R., Mahosky T., Rowan M., Northen T., and Zengler K., 2022, A reproducible and tunable synthetic soil microbial community provides new insights into microbial ecology, Msystems, 7(6): e00951-22.
https://doi.org/10.1128/msystems.00951-22
PMid:36472419 PMCid:PMC9765266

Cowan N., Ferrier L., Spears B., Drewer J., Reay D., and Skiba U., 2022, CEA systems: the means to achieve future food security and environmental sustainability? Frontiers in Sustainable Food Systems, 6: 891256.
https://doi.org/10.3389/fsufs.2022.891256

Dsouza A., Price G., Dixon M., and Graham T., 2021, A conceptual framework for incorporation of composting in closed-loop urban controlled environment agriculture, Sustainability, 13(5): 2471.
https://doi.org/10.3390/su13052471

Engler N., and Krarti M., 2021, Review of energy efficiency in controlled environment agriculture, Renewable and Sustainable Energy Reviews, 141: 110786.
https://doi.org/10.1016/j.rser.2021.110786

Folta K., 2018, Breeding new varieties for controlled environments, Plant Biology, 21(Suppl 1): 6-12.
https://doi.org/10.1111/plb.12914
PMid:30230154

Fonseca-García C., Wilson A., Elmore J., Pettinga D., Mcclure R., Atim J., Pedraza J., Hutmacher R., Egbert R., and Coleman-Derr D., 2023, Defined synthetic microbial communities colonize and benefit field-grown sorghum, bioRxiv, 2023: 542977.
https://doi.org/10.1101/2023.05.30.542977
PMid:37292352 PMCid:PMC10245066

Gan C., Soukoutou R., and Conroy D., 2022, Sustainability framing of controlled environment agriculture and consumer perceptions: a review, Sustainability, 15(1): 304.
https://doi.org/10.3390/su15010304

Imler C., 2020, Quantifying temperature effects in controlled environment agriculture leafy greens and culinary herbs, Iowa State University, pp.1-80.
https://doi.org/10.31274/etd-20210114-67

Lu Y., Gong M., Li J., and Ma J., 2023, Optimizing controlled environmental agriculture for strawberry cultivation using RL-informer model, Agronomy, 13(8): 2057.
https://doi.org/10.3390/agronomy13082057

Luo J., Li B., and Leung C., 2022, A survey of computer vision technologies in urban and controlled-environment agriculture, ACM Computing Surveys, 56(5): 1-39.
https://doi.org/10.1145/3626186

Marie T., Leonardos E., Lanoue J., Hao X., Micallef B., and Grodzinski B., 2022, A perspective emphasizing circadian rhythm entrainment to ensure sustainable crop production in controlled environment agriculture: dynamic use of LED cues, Frontiers in Sustainable Food Systems, 6: 856162.
https://doi.org/10.3389/fsufs.2022.856162

Marín O., González B., and Poupin M., 2021, From microbial dynamics to functionality in the rhizosphere: a systematic review of the opportunities with synthetic microbial communities, Frontiers in Plant Science, 12: 650609.
PMid:34149752 PMCid:PMC8210828

Martins S., Pasche J., Silva H., Selten G., Savastano N., Abreu L., Bais H., Garrett K., Kraisitudomsook N., Pieterse C., and Cernava T., 2023, The use of synthetic microbial communities (SynComs) to improve plant health, Phytopathology, 113(8): 1369-1379.
https://doi.org/10.1094/PHYTO-01-23-0016-IA
PMid:36858028

Niu G., and Masabni J., 2018, Plant Production in Controlled Environments, Horticulturae, 4(4): 28.
https://doi.org/10.3390/horticulturae4040028

Ojo M., and Zahid A., 2022, Deep learning in controlled environment agriculture: a review of recent advancements, challenges and prospects, Sensors, 22(20): 7965.
https://doi.org/10.3390/s22207965
PMid:36298316 PMCid:PMC9612366

Pradhan S., Tyagi R., and Sharma S., 2022, Combating biotic stresses in plants by synthetic microbial communities: principles, applications and challenges, Journal of Applied Microbiology, 133(5): 2742-2759.
https://doi.org/10.1111/jam.15799
PMid:36039728

Sai N., Devi A., and Balachandar D., 2022, Synthetic microbial community (SynCom) for sustainable agriculture, Indian Journal of Plant Genetic Resources, 35(3): 351-354.
https://doi.org/10.5958/0976-1926.2022.00098.5

Shamshiri R., Kalantari F., Ting K., Thorp K., Hameed I., Weltzien C., Ahmad D., and Shad Z., 2018, Advances in greenhouse automation and controlled environment agriculture: A transition to plant factories and urban agriculture, International Journal of Agricultural and Biological Engineering, 11(1): 1-22.
https://doi.org/10.25165/j.ijabe.20181101.3210

Shayanthan A., Ordoñez P., and Oresnik I., 2022, The role of synthetic microbial communities (SynCom) in sustainable agriculture, Frontiers in Agronomy, 4: 896307.
https://doi.org/10.3389/fagro.2022.896307

Souza R., Armanhi J., and Arruda P., 2020, From microbiome to traits: designing synthetic microbial communities for improved crop resiliency, Frontiers in Plant Science, 11: 1179.
https://doi.org/10.3389/fpls.2020.01179
PMid:32983187 PMCid:PMC7484511

Tan B., Li Y., Liu T., Tan X., He Y., You X., Leong K., Liu C., and Li L., 2021, Response of plant rhizosphere microenvironment to water management in soil- and substrate-based controlled environment agriculture (CEA) systems: a review, Frontiers in Plant Science, 12: 691651.
https://doi.org/10.3389/fpls.2021.691651

Tetreault J., Fogle R., Ramos A., and Timmons M., 2023, A predictive model of nutrient recovery from ras drum-screen effluent for reuse in aquaponics, Horticulturae, 9(3): 403.
https://doi.org/10.3390/horticulturae9030403

Trivedi P., Mattupalli C., Eversole K., and Leach J.E., 2021, Enabling sustainable agriculture through understanding and enhancement of microbiomes, New Phytologist, 230(6): 2129-2147.
https://doi.org/10.1111/nph.17319
PMid:33657660

Vishwakarma A., Sahu A., Sheikh N., Payasi P., Rajput S., and Srivastava L., 2020, IOT based greenhouse monitoring and controlling system, In 2020 IEEE Students Conference on Engineering & Systems (SCES), IEEE, pp.1-6.
https://doi.org/10.1109/SCES50439.2020.9236693
PMid:32959124

Wang C., Li Y., Li M., Zhang K., Ma W., Zheng L., Xu H., Cui B., Liu R., Yang Y., Zhong Y., and Liao H., 2021, Functional assembly of root-associated microbial consortia improves nutrient efficiency and yield in soybean, Journal of Integrative Plant Biology, 63(3): 1021-1035.
https://doi.org/10.1111/jipb.13073
PMid:33491865

Wang Z., Hu X., Solanki M., and Pang F., 2023, A synthetic microbial community of plant core microbiome can be a potential biocontrol tool, Journal of Agricultural and Food Chemistry, 71(13): 5030-5041.
https://doi.org/10.1021/acs.jafc.2c08017
PMid:36946724