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Towards sustainable agriculture through synthetic microbial communities: beyond multifunctional roles, integrated applications, and ecological considerations

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Abstract

Agriculture faces significant challenges, including climate change, resource limitations, and land degradation, threatening food security. Traditional practices reliant on chemical inputs are often unsustainable, emphasizing the need for alternative solutions. Synthetic microbial communities (SynComs) are artificially assembled microbial consortia designed to improve plant health, reduce chemical inputs, and enhance soil fertility, responding to the limitations of monoculture systems and synthetic agrochemicals. SynCom holds the transformative potential to drive sustainable agriculture. These consortia can serve as biofertilizers, improving nutrient cycling and stress tolerance. They are also involved in bioremediation, transforming pollutants into non-toxic products, and converting crop residues into valuable bio-based products. Integrating SynComs into agricultural practices has the potential to address environmental challenges, promote sustainable farming, and provide long-term food security and ecosystem health. However, realizing their full capacity requires interdisciplinary research, supportive policy and incentive structures, and engagement with farmers through participatory research and knowledge transfer.

1. Introduction

Today's agriculture faces significant challenges, such as climate change, resource limitations, and land degradation (Shayanthan et al., 2022; El Chami et al., 2020). These issues lead to reduced crop yields and threaten food security, with a projected global population of 9.7 billion by 2050 (Gu et al., 2021). Although pesticides and chemical fertilizers have been utilized in agriculture, their sustainability impacts are increasingly discussed, highlighting the urgent need for more sustainable agricultural practices (Khan, B et al., 2023; Baweja et al., 2020). Microbial communities are key to sustainable farming practices (Cappelli et al., 2022). They enhance soil quality and promote plant growth through secondary metabolites that improve nutrient solubilization, growth regulation, and enzyme production (Meena et al., 2023; Mitra et al., 2022). Synthetic biology applications have promise for addressing these challenges (Valle-García et al., 2023; Tian et al., 2021).

Integrating microbial communities into synthetic microbial communities (SynComs) offers stimulating options in agricultural practices (Gonçalves et al., 2023). SynCom was constructed by understanding microbial functions, which involves identifying those with desirable traits for agricultural use. Each strain is characterized and classified for its specific function before being combined as a SynCom (Johns et al., 2016). Designing SynComs involves systematically integrating microbial species from in *vitro* screening and in *vivo* verification (Shayanthan et al., 2022; Tsolakidou et al., 2019). SynCom design is characterized by plant growth-promoting traits, antagonistic activities, biochemical characteristics, enzyme productions, and insecticidal properties (Yan et al., 2024; Cherif et al., 2022; Vega-Celedón et al., 2021). Selected SynCom involves strain characteristics and construction strategies (Marín et al., 2021).

SynComs have potential applications in biotechnology, agriculture, and environmental science (Singha and Shukla, 2023; Prigigallo et al., 2022). SynComs can be sourced from various collections, including natural environments, extreme conditions like high salinity or drought, or even gene bank collection (De-Lin et al., 2024; Chaudhary et al., 2023; Zhuang et al., 2021; Zhang et al., 2019). Sustainable farming practices focus on improving soil health and reducing harmful pesticides (Saha and Bauddh, 2020). This review thus emphasizes the practical applications of SynComs as crucial resources for enhancing sustainable agriculture and environmental sustainability, highlighting their multifunctional roles, integrated field applications, and ecological considerations.

2. Methodology of literature review

This review aims to synthesize the scientific understanding of synthetic microbial communities' roles, applications, and ecological implications (SynComs) in sustainable agriculture. A structured literature search was conducted across major electronic databases, including Google Scholar, covering publications from 2010 to 2025. The search procedure utilized integrations of relevant keywords such as artificial microbial consortia, engineered microbial consortia, microbial consortium, plant growth-promoting rhizobacteria, and sustainable agriculture. Inclusion criteria were encompassed peer-reviewed original research, book chapters, review articles published in English, relevant institutional reports, and online-accessible sources. Conference abstracts, unpublished theses, and non-English publications were excluded. During the screening phase, titles and abstracts were assessed for relevance, followed by full-text reviews of the articles. Manual data extraction was performed, with studies organized thematically into conceptual domains, including the multifunctional roles of SynComs, their integrated agricultural applications, and the associated ecological implications. The precise investigation was given to identify recent advancements, current research gaps, and the prospects for the practical application of SynComs in sustainable agricultural systems.

3. Approaches for engineering synthetic microbial communities (SynComs)

Synthetic microbial communities (SynComs) can be defined as consortia of microorganisms (Mehlferber et al., 2024). SynCom combines microbial species to address agricultural challenges and enhance crop productivity (Devi and Balachandar, 2022; Karkaria et al., 2021). SynCom's design and construction require analyzing different characteristics (Johns et al., 2016). The selection process, shown in Fig. 1, involves analyzing different strains to isolate those with desirable traits for agriculture. Each strain is characterized and classified by its specific function before being included in the final SynCom. SynComs can be developed from various sources like natural culture collections and gene banks (De-Lin et al., 2024; Zhuang et al., 2021; Zhang et al., 2019). They play a crucial role in promoting plant growth, mainly when sourced from environments with resilient plants (Liu, H et al., 2022). SynComs from healthy rhizospheres enhance crop health and stress tolerance, leading to high yields and disease resistance. Additionally, those derived from extreme conditions such as high salinity or drought can boost plant resilience (Chaudhary et al., 2023).

SynCom construction involves *in vitro* screening and *in vivo* verification. *In vitro* screening identifies microbes with beneficial activities using molecular techniques and culture methods, while *in vivo* testing evaluates these microbes with plants in controlled conditions (Tsolakidou et al., 2019). The results helped create SynComs, which tested greenhouses on

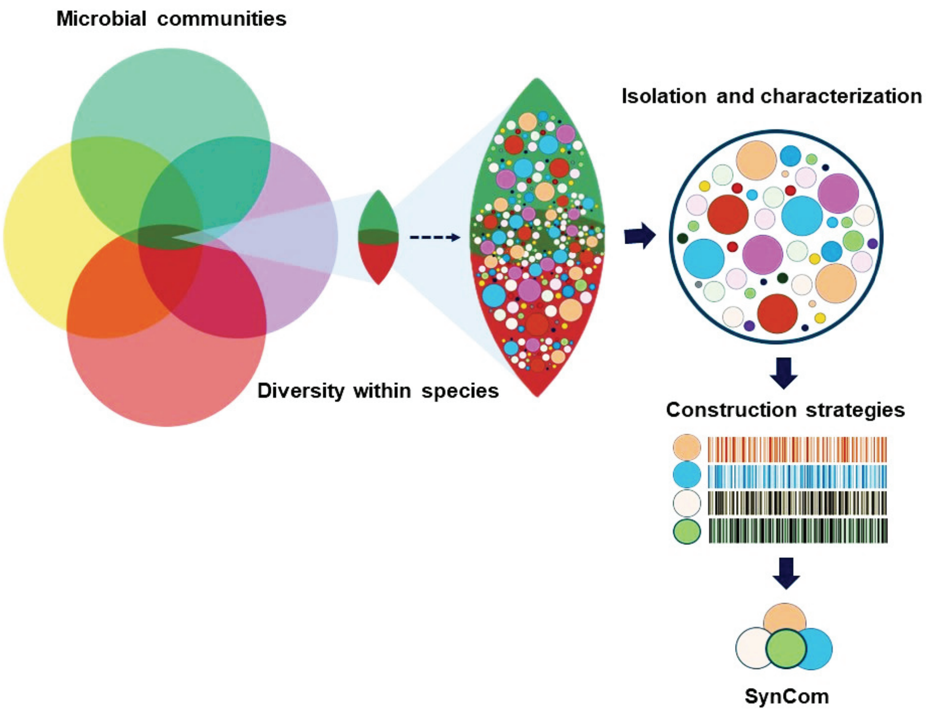

Fig. 1. The process involved in constructing a SynCom. The process begins with various microbial communities, each performing specific functions. Strains are characterized, screened, and isolated based on their functions. Desirable strains for specific applications are selected and constructed into a customized microbial consortium, or SynCom

Table 1
SynComs' wide range of applications illustrates their versatility in addressing various agricultural and environmental challenges. These include enhancing crop resilience, decreasing herbicide needs, developing biocontrol strategies, and advancing biosensor technology

SynComs	Strain sources	Applied applications	Objectives	References
Pseudomonas sp. N4, *Pseudomonas* sp. N8, *Ensifer* sp. N10, *Ensifer* sp. N12	*Medicago* spp. nodules	Biofertilizer and bioremediation	To promote *M. sativa* growth and nodulation in degraded estuarine soils under several abiotic stresses, including high metal contamination, salinity, drought, and temperature.	Flores-Duarte et al., 2023a
Pantoea agglomerans S3, *Bacillus velezensis* R5, *Pseudomonas chlororaphis* H4, *Priestia megaterium* MS2, *Bacillus subtilis* MR4, *Pseudomonas gessardi* MH8	Rhizosphere and tissues of *Mesembryanthemum crystallinum*	Biofertilizer and bioremediation	To determine the effect of the selected consortiums on plant growth, physiology, and metal accumulation.	Flores-Duarte et al., 2023b
A. xylosoxidans Z2K8, *Burkholderia* sp. Z1AL11, *K. variicola* R3J3HD7, *P. ananatis* E2HD8, *P. diazotrophicus* Z2WL1, *P. protegens* E1BL2	Jala maize landrace	Biofertilizer and biocontrol	It is used to promote plant growth and yield and to inhibit fungi.	Sotelo-Aguilar et al., 2023
B. megaterium, *B. pumilus*, *B.aryabhattai*, *B. subtilis*, *B. pseudomycoides*, *B. toyonensis*	Rhizosphere soil of healthy *R. pseudostellariae*	Biofertilizer	To evaluate the effects of *Bacillus* spp. on soil physicochemical properties and plant physiological characteristics.	Yan et al., 2024
Microbacterium sp., *Pseudomonas extremaustralis*, *Bacillus amyloliquefaciens*, *Priestia megaterium*, *Bacillus subtilis*	Soil	Bioremediation	Regulating the bioavailability of heavy metals.	Nie et al., 2023
R. erythropolis (Rh), *P. aeruginosa* (Ps)	Rhizosphere soil	Bioremediation and biofertilizer	To improve rice Aluminium (Al) resistance by optimizing root morphology and improving soil nutrient availability.	Liu, C et al., 2023
Pseudomonas putida KT2440, *Pseudomonas fluorescens* F113, *Pseudomonas fluorescens* SBW25, *Pseudomonas aeruginosa* PAO1	Fields of wheat	Biopesticide	To reduce herbicide consumption.	Hadayat et al., 2024
T. longipile SG1, *T. asperellum* SG4, *T. koningiopsis* SG6, *T. hamatum* SG18, *T. koningii* SG19, *T. hamatum* SG20, *T. longipile* VB6, *T. spirale* VB25, *T. longipile* VB28, *T. spirale* VB33	Mature chestnut orchard for fruit production (*Castanea sativa* Mill.) affected by ink disease and coetaneous mature silver fir stand (*Abies alba* Mill.) affected by root rot caused by *Heterobasidion abietinum*	Biocontrol	To investigate an innovative strategy for the biocontrol of plant disease.	Frascella et al., 2023
E. coli AR1, *E. coli* AR2, *E. coli* AR3	Engineered microbes	Biomedicine	To enhance the viability of engineered microbes in the host's stomach, protecting them from the stress of acidic conditions.	Inda & Lu, 2020
Bacillus subtilis, *Pseudomonas putida*	Engineered microbes	Biosensors	To engineer flavin mononucleotide–based fluorescent proteins that can be used as fluorescent reporters in aerobic and anaerobic biological systems.	Drepper et al., 2007

target crops to assess their impact on growth, yield, and resilience. The findings from these trials further refine SynCom's composition and application. SynComs demonstrate transformative potential in sustainable agricultural and environmental practices, as shown in Table 1, with their diverse applications across various sectors.

For instance, *Pseudomonas* sp. N4, *Pseudomonas* sp. N8, *Ensifer* sp. N10, and *Ensifer* sp. N12 sourced from *Medicago* spp. nodules were constructed to promote *Medicago sativa* growth and nodulation in degraded estuarine soils under several abiotic stresses, including high metal contamination, salinity, drought, and temperature (Flores-Duarte et al., 2023a). *Pantoea agglomerans* S3, *Bacillus velezensis* R5, *Pseudomonas chlororaphis* H4, *Priestia megaterium* MS2, *Bacillus subtilis* MR4, and *Pseudomonas gessardi* MH8 isolated from rhizosphere and tissues of *Mesembryanthemum crystallinum* were combined as a SynCom to determine plant growth, physiology, and metal accumulation (Flores-Duarte et al., 2023b).

Sotelo-Aguilar et al., 2023, created a SynCom using *Achromobacter xylosoxidans* Z2K8, *Burkholderia* sp. Z1AL11, *Klebsiella variicola* R3J3HD7, *Pantoea ananatis* E2HD8, *Phytobacter diazotrophicus* Z2WL1, and *Pseudomonas protegens* E1BL2 to promote plant growth and inhibit fungi. Similarly, *Bacillus megaterium*, *Bacillus pumilus*, *Bacillus aryabhattai*, *Bacillus subtilis*, *Bacillus pseudomycoides*, and *Bacillus toyonensis* isolated from rhizosphere soil of healthy *Radix pseudostellariae* were constructed for investigating soil physicochemical properties and plant physiological characteristics (Yan et al., 2024). SynCom represents a significant advancement in sustainable agriculture, while also ensuring environmental protection.

4. The use of synthetic microbial communities (SynComs) to improve plant health

Switching from chemical to biological methods in agriculture promotes sustainable practices (Mącik et al., 2020). Farmers are increasingly moving towards biological approaches like biopesticides and beneficial microorganisms to mitigate the adverse effects of conventional farming. These methods are less harmful to biodiversity and cause minimal damage to non-target species (Thakur et al., 2020). They also enhance soil health by increasing organic matter and microbial diversity, while chemical inputs can degrade soil quality and fertility (Buta et al., 2021). SynComs are designed combinations of microorganisms used as biofertilizers to enhance soil health and crop yields. They consist of cultured microorganisms with specific traits for targeted functions (Yin et al., 2022).

SynComs are biofertilizers that enhance soil quality and improve nutrient cycling of nitrogen, phosphorus, and potassium (Kabir et al., 2024). They increase nutrient bioavailability through nitrogen fixation, phosphate solubilization, and mobilization of other nutrients, which boosts plant growth (Kaur, S et al., 2022). Additionally, SynComs produce phytohormones such as auxins, cytokinins, gibberellins, ethylene, and abscisic acid, which promote plant growth, root development, and yield (Qiao et al., 2024). Plants use various hormones to regulate growth and development (Singh and Roychoudhury, 2023). Auxins promote cell elongation and root growth for better access to water and nutrients (Jankovska-Bortkevič et al., 2023). Cytokinins drive cell division and enhance shoot growth (Svolacchia and Sabatini, 2023). Gibberellins stimulate stem elongation, seed germination, and flowering (Ritonga et al., 2023). Ethylene aids fruit ripening and manages root development and stress responses (Huang et al., 2023). Meanwhile, SynComs also release abscisic acid to help plants cope with drought and salinity (Segarra-Medina et al., 2023).

Furthermore, SynCom produces several substances that enhance plant growth and health. One key component is siderophores, which chelate iron in the soil, making it accessible for essential metabolic processes like photosynthesis (Misra et al., 2023). They also solubilize potassium, phosphorus, and zinc, improving nutrient availability (Bakki et al., 2024). Additionally, SynComs generates antibiotics to protect plants from harmful microbes, reducing disease and promoting overall health (Hansen et al., 2023). They contain enzymes that break down soil organic matter, release nutrients (Chiaranunt and White, 2023), and produce volatile organic compounds that stimulate growth and activate defenses against pathogens (Jing et al., 2024).

The Fig. 2 illustrates how SynComs function as biofertilizers to enhance plant growth. The interaction between host plants and SynComs involves signaling and material exchange. When plants release sugars and amino acids from their roots, SynComs are attracted and secrete signaling molecules recognized by the plants. They then colonize the root surface or interior, transferring beneficial metabolites. For growth, plants need macronutrients (N, P, K) and micronutrients (Fe, Zn, Cu). The SynCom colonizes the roots and surrounding soil, improving nutrient availability through nitrogen fixation, P, K, and Zn solubilization, and iron chelation. In turn, plant roots absorb these nutrients and facilitate microbial interactions. Additionally, SynCom produces compounds like hormones and antimicrobial agents that promote growth, enhance stress resistance, and suppress pathogens. SynComs can also form biofilms on roots, creating a protective microenvironment that facilitates nutrient exchange and shields against pathogens, ultimately promoting plant growth significantly.

SynComs release phytohormones and growth-promoting substances into the soil, enhancing plant nutrient absorption. For instance, phosphorus-solubilizing bacteria convert insoluble phosphorus into soluble forms for easier uptake (Zhou et al., 2024). Some SynCom members decompose organic matter, releasing nutrients (Cao et al., 2023). The compounds secreted can penetrate root cell membranes, and some volatile substances can be absorbed by leaves (Zhang et al., 2024). Denaya et al. (2021) showed that a SynCom of *Citrobacter braakii*, *Citrobacter freundii*, and *Pseudomonas stutzeri* significantly enhances plant growth by improving nutrient uptake and inducing resistance against pathogens. Similarly, Kaur, T et al. (2022) found a SynCom of *Erwinia* sp. EU-B2SNL1, *Chryseobacterium arthrosphaerae* EU-LWNA-37, and *Pseudomonas gessardii* EU-MRK-19 further boosts plant growth, nutrient uptake, disease resistance, and stress tolerance.

Fig. 2. SynCom enhances nutrient acquisition and promotes plant health within the rhizosphere. SynCom's members colonize plant roots and improve nutrient availability through nitrogen fixation, solubilization, iron chelation, hormones, and antimicrobial agents that enhance growth, stress resistance, and disease suppression. Schematic of a root section showing the structure of the rhizosphere was sourced from the Nature Education Knowledge Project (https://www.nature.com/scitable/knowledge/library/the-rhizosphere-roots-soil-and-67500617/, accessed on January 11, 2025)

The development of SynCom as a biofertilizer leveraging PGP traits offers a promising method for enhancing nutrient availability in soil. Selecting isolated strains with strong PGP trait performance can improve soil properties and plant growth. Verma et al. (2018) developed a SynCom of *Bacillus subtilis* BHUJP-H1, *Bacillus* sp. BHUJP-H2 and *Bacillus licheniformis* BHUJP-H3, based on biochemical characterization and plant growth-promoting traits. These traits, including catalase, cellulase, and phosphate solubilization, significantly enhance the growth of *Vigna radiata*.

Current studies indicate that constructing SynComs as biofertilizers requires selecting specific bacterial strains based on their PGP traits (Srivastava and Sharma, 2022). As shown in Table 2, the formulation relies on evaluating PGP traits, antagonistic activities, biochemical characteristics, and hydrolytic enzyme production (Kaur et al., 2024; Mir et al., 2024; Devi, R et al., 2022a; Devi, R et al., 2022b; Kumar et al., 2021). These traits enhance nutrient absorption, with certain strains capable of capturing atmospheric nitrogen and converting it into ammonia, thereby increasing soil nitrogen content. They also can convert essential nutrients like phosphate, potassium, and zinc into soluble forms, enhancing their availability to plants. Additionally, SynCom produces phytohormones and growth regulators that support plant growth, promote resilience against environmental stress, and improve overall health and productivity. These traits enable SynComs to contribute to more sustainable agricultural systems. Utilizing SynCom in biofertilizers supports sustainable agriculture, boosts crop productivity, and enriches soil quality, making it a valuable advancement of farming practices. Thus, using SynCom-based biofertilizers promotes sustainable agriculture and reduces ecological impact.

Table 2
SynComs are constructed as biofertilizers to enhance soil health and crop yields

SynComs	Selection Criteria	Strain Sources	Species indicator	References
Bacillus spp., *Streptomyces* spp., *Azotobaacter* spp., *Frauteria* spp.	PGP traits (Hydrogen cyanide, ammonia production, cellulase, pectinase, protease, amylase, and antagonistic activity).	Soil samples	*Vigna mungo* L.	Maiyappan et al., 2010
B. megaterium, *A. chlorophenolicus*, *Enterobacter*, *P. aeruginosa*	Biochemical characterization and PGP traits (indole-3-acetic acid (IAA), hydrogen cyanide (HCN), siderophore production, P-solubilization, and N-fixation).	Rhizospheric soil samples	*Triticum aestivum*	Kumar et al., 2021
Bacillus subtilis BHUJP-H1 (KU312403), *Bacillus* sp. BHUJP-H2 (KU312404) and *B. licheniformis* BHUJP-H3 (KU312405)	Biochemical characterization and PGP traits (Catalase, cellulase, amylase, indole-3-acetic acid, phosphate solubilization, production of ammonia, siderophore, and hydrogen cyanide).	Soil and water samples	*Vigna radiata*	Verma et al., 2018
Pseudomanas gessardi EU-LWNA-25 and *Erwinia rhapontici* EU-B1SP1	PGP traits (N-fixation, solubilization of K, P, and Zn; siderophores, ammonia, indole-3-acetic acid, 1-aminocyclopropane-1-carboxylic acid, and hydrogen cyanide production).	Rhizospheric soil samples	*Amaranthus hypochondriacus* L.	Devi, R et al., 2022a

Table 2 – continue

SynComs	Selection Criteria	Strain Sources	Species indicator	References
Ensifer adhaerens strain BK-30, *Pseudomonas fluorescens* strain SN5, and *Bacillus megaterium* strain SN15	Using concentrations of sodium chloride (NaCl), ACC-deaminase activities, Phosphate solubilization, and Indole acetic acid production.	Rhizospheric soil samples	*Triticum aestivum*	Khan et al., 2022
K. oryzendophytica YMA7, *P. kribbensis* KSB, *P. polymyxa* COW3	PGP traits (P-solubilizing, K-solubilizing, N-fixing, IAA-producing, ammonia production, Production of Indole-3-Acetic Acid, Siderophore production, and antagonistic activities).	Rhizospheric soil samples	*Oryza sativa*	Sherpa et al., 2021
Enterobacter ludwigii EU-BEN-22, *Micrococcus indicus* EU-BRP-6, *Pseudomonas gessardii* EU-BRK-55	PGP traits (Nitrogen-fixing, phosphorus solubilization, potassium solubilization).	Rhizospheric soil samples	*Solanum melongena* L.	Kaur et al., 2024
Erwinia persicina EU-A3SK3, *Halomonas aquamarina* EU-B2RNL2, and *Pseudomonas extremorientalis* EU-B1RTR1	PGP traits (Phosphorus solubilization, Potassium solubilization, nitrogen fixation, solubilization of zinc; production of siderophores, IAA, ammonia, and hydrogen cyanide).	Rhizospheric soil and root samples	*Capsicum annum* L.	Devi, R et al., 2022b
Azotobacter chroococcum, *Priestia megaterium,* and *Pseudomonas* sp. SK3	PGP traits (indole-3-acetic acid (IAA) production, Siderophore production, HCN production, Ammonia production, ACC deaminase activity, solubilization of phosphate, amylase production, Production of exopolysaccharide, and zinc solubilizing).	National Bureau of Agriculturally Important Microorganisms (NBAIM) Mau, Uttar Pradesh, India, and Culture Bank in Environmental Genomics Laboratory, Indian Institute of Technology, Delhi.	*Cajanus cajan*	Srivastava & Sharma, 2022
Streptomyces sp. Al-Dhabi 30, *Lactobacillus plantarum* ATCC 33222, and *Candidautilis* ATCC 9950	PGP traits (phosphate solubilization, production of siderophores, indole acetic acid), Hydrolytic enzyme (chitinase, cellulase, pectinase, and protease), and antagonistic activities.	Rhizospheric soil samples	*Solanum lycopersicum*	Al-Dhabi et al., 2019
Pseudomonas sp. TmR5a and *Curtobacterium* sp. BmP22c	PGP traits (IAA production, phosphate solubilization, presence of nifH (nitrogenase reductase) and acdS (1-aminocyclopropane-1-carboxylate (ACC) deaminase) genes, and anti-phytopathogenic activities).	Soil samples	*Solanum lycopersicum*	Vega-Celedón et al., 2021
Rhizobium tropici IHTF-1 and *Rhizobium mayense* IHTF-2	PGP traits (indole-3-acetic acid (IAA), solubilization of minerals like phosphate, potassium and zinc, siderophore, ACC deaminase, and ammonia), and hydrolytic enzymes (chitinase, β- 1, 3-glucanase and cellulase).	Root nodules	*Phaseolus vulgaris* L.	Mir et al., 2024
Serratia marcescens 59, *Pseudomonas fluorescens* 57, *Rahnella aquatilis* 36 and *Bacillus amyloliquefaciens* 63	PGP traits (Indole acetic acid (IAA) production, Phosphate solubilization, Chitinases production), and *in vitro* antagonistic activity.	Rhizospheric soil samples	*Cicer arietinum* L.	Palmieri et al., 2017
Pseudomonas aeruginosa B4, *Pseudomonas aeruginosa* B23, *Pseudomonas aeruginosa* B25, *Pseudomonas aeruginosa* B35, *Serratia marcescens* B8 and *Alcaligenes feacalis* B16	PGP traits (siderophore, IAA, HCN, and chitinolytic activities), and antagonistic assay.	Rhizospheric soil samples	*Solanum tuberosum* L.	Devi et al., 2018
Brevibacillus fluminis, *Brevibacillus agri* and *Bacillus paralicheniformis*	PGP traits (catalase test, glucose fermentation, IAA test, H_2S production, starch hydrolysis, tween 80, gelatin hydrolysis, casein hydrolysis, P solubilization, Zn solubilization, and ammonia production).	Soil samples	*Solanum melongena, Solanum tuberosum, Solanum lycopersicum,* and *Capsicum frutescens*	Goswami et al., 2019

5. Integrated application of synthetic microbial communities (SynComs) reduces the consumption of pesticides

Insects can damage crops and lead to agricultural losses (Snyder et al., 2020). While chemical pesticides are commonly utilized to control pests, their harmful effects on health and the environment raise concerns (Buta et al., 2021). Pesticides can harm non-target species, disrupt ecological balance, and adversely affect soil health by reducing beneficial organism activity, compromising nutrient cycling and soil stability. Additionally, they can contaminate groundwater and water bodies through runoff, threatening drinking water sources and aquatic ecosystems and leading to food chain accumulation (Kumar, P et al., 2023). Pesticides can release volatile organic compounds (VOCs) that react with nitrogen oxides (NOx) to create ground-level ozone, a harmful component of smog linked to respiratory issues (Zhou et al., 2023). VOCs can travel long distances, making pesticides widely impactful. They pose immediate risks, such as skin irritation and poisoning, and long-term exposure can lead to serious health problems, including cancer and neurological disorders (Dhankhar and Kumar, 2023).

Scientific research seeks to balance agricultural productivity with environmental and human health through sustainable methods. Biological pest control, particularly microbial pesticides, is a promising solution. These pesticides are targeted, ecologically safe, and support beneficial insects, enhancing biodiversity (Rodrigues et al., 2023). Utilizing SynComs as biopesticides can lessen the environmental impact of chemical pesticides and reduce risks like soil degradation and water contamination (Sharma, 2023). SynComs can produce harmful endotoxins that affect insect larvae when ingested (Seenivasagan and Babalola, 2021; Pathma et al., 2021). These proteins become active and soluble in the gut due to digestive enzymes and alkalinity, damaging the gut lining and stopping the larvae from feeding. The toxins attach to specific receptors in the gut cells, causing paralysis and ultimately leading to starvation and death (Baranek et al., 2023; Konecka et al., 2012).

Microbes are used as biopesticides for pest control, with commonly applied strains including *Bacillus thuringiensis* (or *Bt*), *Pseudomonas*, *Beauveria*, *Metarhizium*, and *Trichoderma* (Batista and Singh, 2021). A study showed that a SynCom of *Paranosema locustae* and *Beauveria bassiana* effectively controls grasshoppers (Tan et al., 2021). *P. locustae* weakens the host, while *B. bassiana* multiplies inside and feeds on it, making this SynCom approach an innovative and eco-friendly method for managing grasshopper populations.

In the case study by Spescha et al. (2023), a SynCom was developed to biologically control the cabbage maggot (*Delia radicum*), a pest damaging Brassicaceae crops. The SynCom combined the bacterium *Pseudomonas chlororaphis*, nematode *Steinernema feltiae*, and fungus *Metarhizium brunneum*. *P. chlororaphis* was included for its pest and disease resistance, while *S. feltiae* and *M. brunneum* were commercially used. The results indicated a 50% reduction in pest survival and maggot damage to radish bulbs (Spescha et al., 2023).

Olanrewaju and Babalola (2019) reported that a SynCom of *Bacillus subtilis* A1, *Pseudomonas* sp. A18, *Pseudomonas* sp. A29, *Streptomyces globisporus* NWU4, *Streptomyces griseoflavus* NWU14, and *Streptomyces heliomycini* NWU198 were effective against the fungal pathogen *Fusarium graminearum*. The study revealed that this SynCom produces antimicrobial compounds that inhibit *F. graminearum* growth (Olanrewaju and Babalola, 2019). *B. subtilis* is known for lipopeptides like iturin and surfactin, which have strong antifungal properties. Similarly, *Streptomyces* species and *Pseudomonas* strains produce natural antibiotics and compounds that disrupt fungal cell membranes and respiration, effectively combatting fungal infections. Thus, SynComs can control pests and plant pathogens, helping to address productivity challenges while minimizing environmental impacts.

6. The enhancement of plant disease resistance, stress tolerance and soil fertility

Plant diseases significantly affect plant health and productivity, often caused by pathogens like fungi, bacteria, viruses, and nematodes (Nazarov et al., 2020; Shinwari et al., 2019). Common agricultural diseases include fungal infections like powdery mildew and rust, bacterial diseases like fire blight, and nematode infestations. Symptoms include leaf or fruit spots, wilting, stunted growth, and root decay (Tripathi et al., 2022). These issues disrupt photosynthesis and nutrient absorption, significantly reducing plant productivity. Meanwhile, plant stress can adversely affect growth, reproduction, and overall productivity due to various physiological and molecular changes, threatening plant health and survival (Zandalinas et al., 2021). Stress can be categorized as abiotic or biotic. Abiotic stress is caused by non-living factors such as temperature extremes, drought, soil deficiencies, and chemical exposure. Biotic stress stems from living organisms, including pests and diseases (Nawaz et al., 2023; Das and Biswas, 2022; Mahmoud, 2021). Both types of stress can significantly reduce photosynthetic efficiency, ultimately decreasing crop yield and quality.

Excessive chemical fertilizers can harm soil health by reducing fertility and organic matter and disrupting microbial communities (Pahalvi et al., 2021). While these synthetic compounds provide essential nutrients like nitrogen, phosphorus, and potassium to increase crop yields, their overuse and improper disposal have adverse environmental effects (Pahalvi et al., 2021). Chemical fertilizers high in nitrogen can lower soil pH through nitrification, leading to acidification. This acidity can limit access to essential nutrients like phosphorus and increase harmful metal solubility, reducing soil fertility (Zhang et al., 2022). Additionally, these fertilizers disrupt soil microorganisms that decompose organic matter, decreasing microbial diversity and activity. Consequently, less organic matter is converted into humus, which is important for maintaining soil fertility (Sabir et al., 2021).

Utilizing a biological approach to enhance soil quality is recommended as it can help mitigate negative impacts. Recent studies highlight the potential of SynComs in enhancing plant resistance to diseases and stress (De Souza et al., 2020). These microbial communities produce proteinaceous toxins that inhibit harmful bacteria and polyketides and are effective against various bacterial diseases (Li and Honda, 2021; Bonaterra et al., 2022). Additionally, they contain hydrolytic enzymes like chitinases, glucanases, and proteases that break down fungal cell walls (Wang et al., 2021). SynComs also improve plant health and resilience by enhancing nutrient availability and generating phytohormones (Mukherjee et al., 2021). SynComs play a vital role in nutrient cycling, organic matter decomposition, and promoting plant growth (El Hamss et al., 2023; Kumar and Verma, 2019). A 2024 study by Lyu et al. highlights that SynComs can decompose organic matter, providing nutrients to plants in easily digestible forms (Lyu et al., 2024). Plants absorb carbon dioxide and water, converting them into glucose and oxygen through photosynthesis. Nitrogen and phosphorus are crucial for plant nutrition. Nitrogen is essential for amino acids and protein synthesis, while phosphorus is vital for energy transfer and is a key component of nucleic acids and cell membranes (Zheng et al., 2023; Khan, F; Shah et al., 2024).

Zhuang et al. (2021) found that a SynCom of six *Pseudomonas* strains can enhance plant growth and disease resistance. Similarly, Ma et al. (2023) showed that a SynCom with *Bacillus* sp., *Burkholderia* sp., *Pseudomonas* sp., *Streptomyces* sp., and *Bradyrhizobium* sp. effectively controls *Fusarium oxysporum* by boosting the defense enzyme activity. In 2022, Kaur et al. studied the SynComs, consisting of *Arthrobacter* sp., *Enterobacter* sp., *Brevibacterium* sp., and *Plantibacter* sp., in enhancing soil health and crop productivity. The study found that SynCom improved soil nitrate availability by 55%, germination rates by 14.3%, plant height by 7.4%, and shoot biomass by 5.4% (Kaur, S et al., 2022). These results suggest that SynComs can enhance nutrient cycling and promote sustainable agriculture, highlighting their potential to improve soil fertility and crop productivity. Hence, SynComs offers a multifaceted approach to improving plant resilience and agricultural practices.

7. Bioremediation of hazardous pollutants from agricultural soils

Farming practices and industrial activities introduce toxic pollutants like heavy metals and pesticides into soils, risking soil and water quality, food safety, and human health (Rashid et al., 2023; Alengebawy et al., 2021). These pollutants disrupt the soil ecosystem and reduce fertility. Bioremediation is an effective strategy to address environmental pollution. Recently, SynComs used natural metabolic pathways to degrade pollutants into less harmful substances, converting them into nutrients or energy for growth (Lashani et al., 2023; Li et al., 2021). SynComs actively biotransform contaminated soils, helping in the in situ degradation of hazardous materials. Each species in SynComs utilizes specific metabolic pathways and enzymatic systems to break down contaminants and detoxify them. These processes transform pollutants into non-toxic products, enhancing environmental restoration and soil health, as shown in Fig. 3. Through microbial metabolism, SynComs can break hazardous compounds into simpler, less harmful intermediates. The enzymes produced by SynComs promote the detoxification process by catalyzing the degradation of pollutants into benign components such as water, carbon dioxide, or simpler organic molecules. As a result of both microbial degradation and enzymatic activity, toxic compounds are converted into harmless substances. These non-toxic byproducts can seamlessly integrate into natural biogeochemical cycles without causing adverse effects.

Chaudhary et al. (2023) found that a SynCom of *Pseudomonas pseudoalcaligenes*, *Micrococcus luteus*, *Bacillus* sp., and *Exiguobacterium aurantiacum* effectively removed oligotrophic pesticides from polluted lakes (Chaudhary et al., 2023). These bacteria utilize pollutants as nitrogen sources for growth, with various enzymes, including esterase, peptidase, urease, and thioesterase, aiding in pesticide degradation (Malik et al., 2022). Furthermore, Abraham et al. (2014) found that SynCom includes *Alcaligenes* sp. JAS1 and *Pseudomonas moraviensis* JAS18

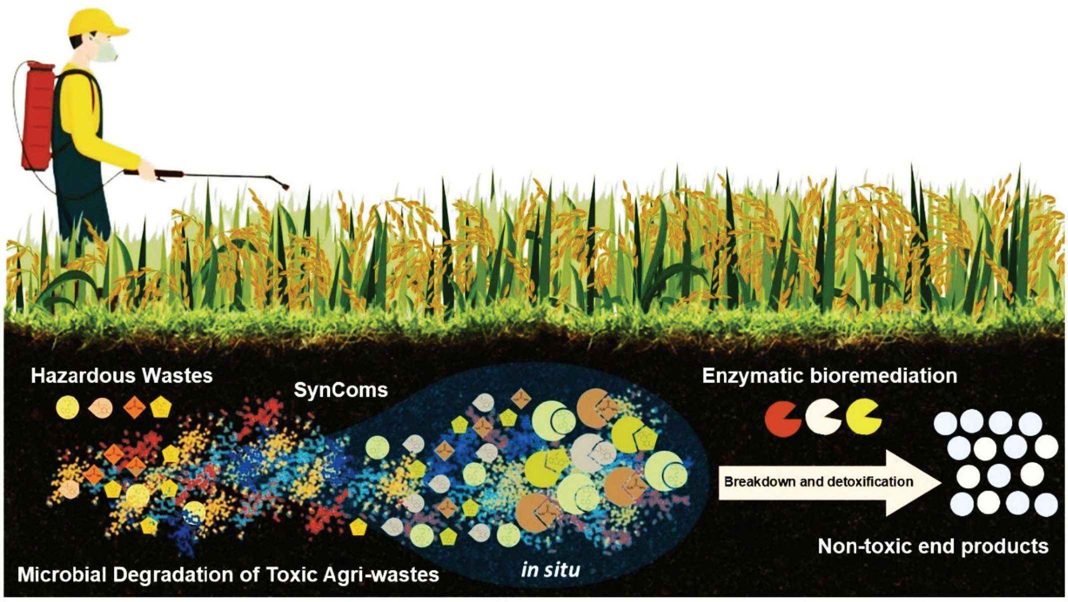

Fig. 3. SynComs break hazardous compounds into simpler ones through microbial metabolism. Enzyme detoxification catalyzes pollutants into non-toxic byproducts that can seamlessly integrate into natural biogeochemical cycles without causing adverse effects

effectively degrade organophosphorus and organochlorine pesticides. Each strain can break down these pesticides. Phosphotriesterase from *Pseudomonas* sp. targets organophosphorus pesticides, while dehalogenases from *Alcaligenes* sp. remove chlorine from organochlorine pesticides (Aswathi and Sukumaran, 2019; Furukawa, 2018).

SynCom transforms toxic pesticides into less harmful substances through biochemical mechanisms, primarily enzymatic degradation. Enzymes like hydrolases degrade organophosphates by hydrolyzing chemical bonds (Bhatt et al., 2021). Oxidoreductases can detoxify organic pesticides by adding or removing electrons (Alneyadi et al., 2018). Certain strains in SynCom produce dehalogenase enzymes that eliminate halogen atoms from organochlorine pesticides, significantly reducing toxicity and increasing degradation susceptibility (Buryska et al., 2018). Research indicates that SynComs can effectively break down pollutants, as shown by Lü et al. (2024). These microorganisms possess unique metabolic pathways that convert harmful substances into safer compounds, making them an eco-friendly solution for bioremediation. Therefore, SynComs are designed to break down agricultural chemical pollutants and convert complex compounds into non-toxic substances. Their success in transforming pollutants into non-toxic forms has been demonstrated in lab settings and practical applications.

8. Bioconversion of agricultural residues and waste to value-added products

Crop residues are a valuable yet challenging resource for agriculture and environmental management (Duarah et al., 2022). They are essential for energy generation, material production, and soil enrichment. Microbial processes, particularly SynComs, offer innovative solutions for utilizing these residues through biorefinery methods (Lin et al., 2024). SynComs convert agricultural residues into valuable chemicals via enzymatic hydrolysis and fermentation, starting with the breakdown of polymers into simpler molecules for bacterial consumption. Cellulases break down cellulose into glucose, while hemicellulases degrade hemicellulose into sugar monomers like xylose. Ligninases, such as laccases and peroxidases, decompose lignin, which is more resistant to degradation than cellulose and hemicellulose (Nargotra et al., 2022). After converting biomass into simple sugars, SynCom ferments these sugars under anaerobic or aerobic conditions to produce valuable products. SynCom's metabolic pathways generate biofuels, biochemicals, bioenergy carriers, and pharmaceuticals, as demonstrated in Fig. 4. SynComs convert lignocellulosic residues rich in cellulose, hemicellulose, and lignin into valuable bio-based products. Enzymes such as endoglucanase, exoglucanase, and β-glucosidase

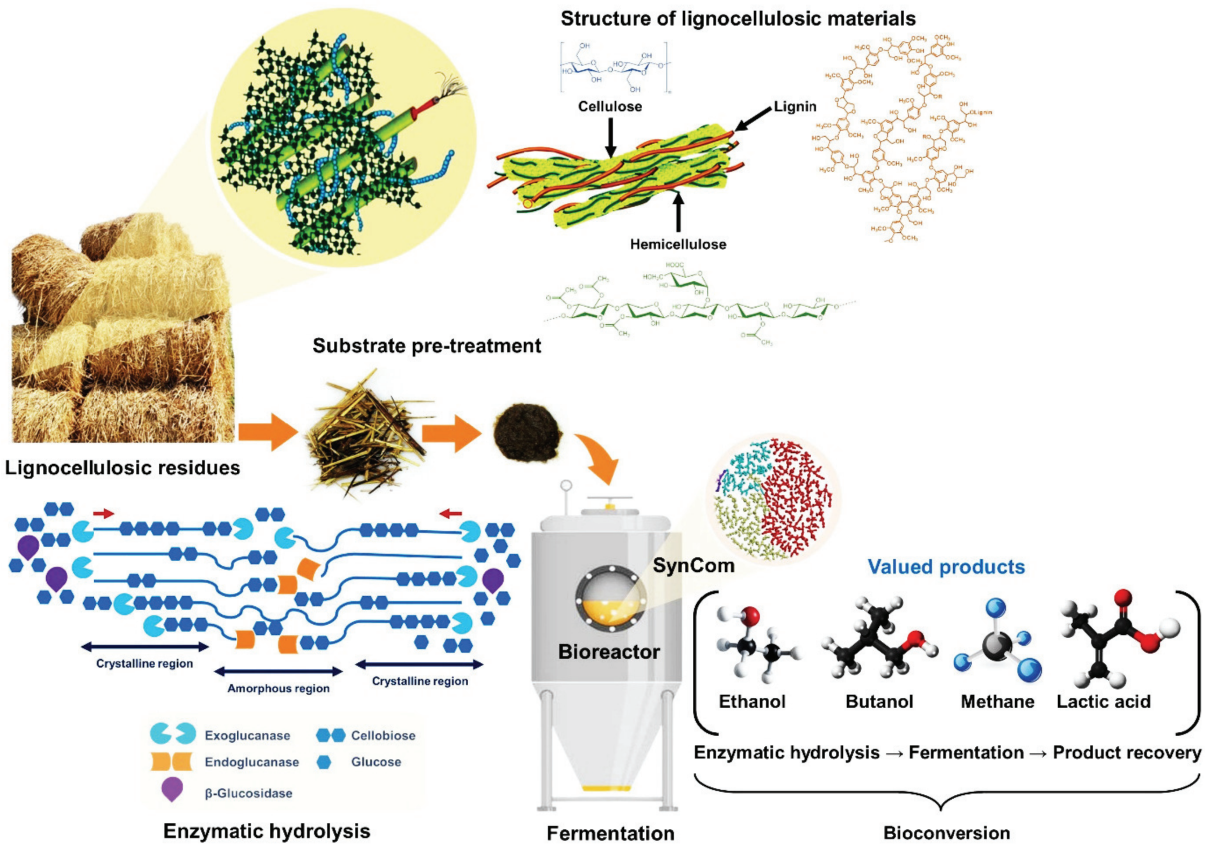

Fig. 4. Lignocellulosic residues rich in cellulose, hemicellulose, and lignin are valuable bio-based products. Pretreatment promotes the release of cellulose and hemicellulose and reduces lignin content. Enzymes like endoglucanase, exoglucanase, and β-glucosidase effectively break cellulose into glucose molecules. SynComs efficiently ferment the resulting sugars into a range of bio-based products. Cellulose, hemicellulose, lignin in plant cells, and the structure of lignocellulosic biomass were sourced from Wang et al., 2017 and Jensen et al., 2017, respectively

effectively degrade cellulose into glucose molecules by targeting cellulose's crystalline and amorphous regions. SynComs then efficiently ferment the resulting sugars into a range of bio-based products. These include ethanol (a biofuel), butanol (both a solvent and biofuel), methane (a renewable energy source), and lactic acid (a precursor for bioplastics). The production of these products occurs through fermentation, followed by recovery in the post-processing phase.

Various SynComs that can break down lignocellulosic residue have been identified (Lin, 2022). Significant progress has been made in using SynComs to convert biomass into valuable products. For instance, Zheng et al. (2020) studied a SynCom of Parabacteroides, Alcaligenes, *Lysinibacillus*, Sphingobacterium, and Clostridium, which efficiently degraded rice straw, resulting in a loss of 71.7% cellulose, 65.6% hemicelluloses, and 12.5% lignin. Fermentation produced acetic acid and butyric acid. Similarly, Dash et al. (2022) found a SynCom of *Penicillium* sp. LF3, *Alternaria alternata* LF9, *Bacillus cereus* LB8, and Enterobacteriaceae bacterium LB18 generated *β*-glucosidase, cellulase, and laccase while decomposing rice straw, releasing methane and carbon dioxide in the process. SynComs' innovative methods can transform biological materials into valuable products, contributing to the circular economy by turning agricultural and industrial waste into resources vital for the biorefinery industry.

9. Challenges of SynCom for sustainable agricultural practices

While SynComs can enhance plant growth, reduce chemical input needs, and improve disease resistance; however, their complex interactions with the environment and the challenges of translating laboratory results to field conditions present difficulties. Their effectiveness faces challenges, including interactions with the native plant microbiome, which can be influenced by soil type, climate, and existing microbial communities (Brooks and Alper, 2021; Burman and Bengtsson-Palme, 2021). Producing and applying SynComs cost-effectively is essential for competition with conventional agricultural inputs, and their widespread adoption depends on this (Tariq et al., 2025; Delgado-Baquerizo et al., 2025). Effectively utilizing SynComs

Table 3
The scientific and economic reasons for using SynComs effectively compete with traditional agricultural inputs, such as chemical fertilizers and pesticides

Challenges faced	Scientific and economic rationales
Economic competitiveness	The substantial initial costs associated with research and development (R&D) for SynCom, including strain isolation, screening, compatibility testing, and formulation, must be balanced by an affordable deployment in the field. If SynCom continues to be priced high, farmers will likely resort to cheaper synthetic agrochemicals, which provide immediate and visible results at a predictable cost.
Cost-efficiency in input use	In theory, SynComs integrates multiple strains, each possessing distinct plant-beneficial traits such as nitrogen fixation, phosphorus and potassium solubilization, and biocontrol. However, certain strains may interact negatively, diminishing functional output. Moreover, results observed in laboratory or greenhouse settings often fail to replicate under field conditions, particularly when considering varying soil types, crops, and climate zones. When formulations are complex or costly, farmers tend to be cautious about decreasing chemical inputs unless a new product can guarantee an equivalent or superior return on investment.
Field consistency and efficacy	Inconsistent field performance poses a significant challenge to the adoption of microbial technology. Native soil microbial communities are inherently diverse and specific to their environmental context. When SynComs are introduced, they often struggle to establish dominance due to competition, predation, or incompatibility. For instance, a SynCom that proves effective in loamy soil may be ineffective in environments characterized by acidic, phosphorus-depleted conditions. Field conditions often involve fluctuating temperature, pH, moisture, salinity, texture, and UV exposure, which can impact microbial viability and, consequently, lead to a loss of function in the field. Additionally, different crops and various cultivars of the same species exhibit distinct rhizosphere exudate profiles that influence their ability to contact SynCom members. What works for SynCom in tomato (*Solanum lycopersicum*) may not apply to maize (*Zea mays*). Consequently, low colonization efficiency can result in weak or absent plant responses.
Integration with existing practices	Conventional inputs like urea and pesticides can be easily applied using standard methods. In contrast, SynComs often necessitate precise placement, such as near plant roots, or require moist conditions to maintain viability. As a result, farmers may need to adjust their routines, invest in new equipment, or modify application timings, which adds to labor and operational complexity. While chemical fertilizers and pesticides are stable under high pressure in sprayers, UV exposure, and temperature fluctuations, SynComs can lose their viability when applied with conventional machinery unless protective formulations are used. Furthermore, they may be negatively impacted or killed by residual pesticides or herbicides, high salinity from fertilizers, or pH levels resulting from chemical soil amendments. SynComs cannot be combined directly with fungicides, insecticides, or synthetic fertilizers, unlike chemical mixes. Conventional agrochemicals typically remain stable for 1 to 3 years at room temperature. In contrast, SynComs require refrigeration and moisture control and have a shorter shelf-life, often around 3 to 6 months for some products. Consequently, storage and logistics have become more complex and costly, particularly in rural or resource-limited settings.

Table 3 – continue

Challenges faced	Scientific and economic rationales
Environmental and regulatory incentives	Although SynComs has the potential to support sustainability goals, they encounter several challenges before they can qualify for carbon credits, eco-labels, or subsidies. Unlike synthetic fertilizers and pesticides, SynComs are often situated in ambiguous regulatory frameworks in many countries (see Table 4). Most national laws lack standardized definitions or approval processes for SynComs. This legal ambiguity prevents them from accessing subsidy programs and claiming the benefits of eco-certification. Even if SynComs contributes to emission reductions, such as through decreased fertilizer usage, no established methodologies for measuring this impact or protocols for verification and certification exist. As a result, farmers who utilize SynComs cannot monetize the environmental benefits without formal recognition within carbon accounting systems. Additionally, without field data analysis, SynComs cannot demonstrate eligibility for eco-labels or market premiums (e.g., Rainforest Alliance, EU Organic). Even when SynCom producers strive to comply with standards like OMRI (US organic list), JAS (Japan organic), and REACH (EU chemical safety), the expenses associated with testing, documentation, and registration can be prohibitively high, particularly for start-ups or small biotech companies. These costs hinder the affordability of SynComs, complicating their cost-effective deployment. Furthermore, market adoption remains limited without adequate training, field demonstrations, and awareness of incentives, even in regions advocating for green agriculture.
Return on investment (ROI)	Creating effective SynComs requires several steps, including genome sequencing, trait screening (such as PGP traits and antagonism), compatibility testing, field trials, and formulation and shelf-life assessments. As a result, SynCom products can be more expensive than conventional inputs, particularly during the initial commercialization phase. If the cost surpasses US$30 per hectare, SynComs may become less economically appealing, even if they offer environmental advantages.

cost-efficiently is crucial for competing against traditional agricultural inputs, such as chemical fertilizers and pesticides. The Table 3 presents the scientific and economic rationale for successfully employing SynComs to rival conventional agricultural practices. Additionally, Table 4 outlines the country-specific barriers to adopting SynComs, primarily stemming from their limited field efficiency and the potential for unpredictable interactions with native microbiomes. This raises concerns regarding long-term stability and environmental impact. Finally, Table 5 compares the functional, environmental, and

Table 4
Country-level barriers to SynCom adoption. SynComs' core barriers are their limited field efficiency and the potential for unpredictable interactions with native microbiomes, leading to concerns about long-term stability and environmental impact.

Country/Region	Main Problem	Barrier for SynComs	Source
Japan	Regulatory ambiguity	Japan has no clearly defined classification for SynComs within the existing fertilizer or pesticide regulations, complicating their approval for widespread agricultural use or organic farming.	(Yokoyama, 2023)
United States	Strict EPA and OMRI listing requirements	SynComs must be categorized as either biostimulants or biopesticides. Multifunctional SynComs do not fit into defined legal categories and incur high regulatory costs.	(Sachs et al., 2020)
European Union	Fragmented implementation of the new EU Fertilizing Products Regulation (FPR)	FPR (EU 2019/1009) favors mono-strain bio-inputs. SynComs, with multiple strains and functions, require more data for efficacy and safety, slowing their approval.	Regulation (EU) 2019/1009
India	Low farmer awareness, weak biofertilizer regulation enforcement	While India promotes bio-inputs, inadequate farmer training and low-quality or unverified microbial products erode trust in SynComs.	(Anisha & Pooja, 2023)
China	Regulatory lag and emphasis on chemical fertilizers in subsidy schemes	Although there is interest in green agriculture, SynComs is not yet prioritized in policy or government procurement compared to conventional fertilizers.	(Fang, 2018)
Brazil	Stringent approval under MAPA (Ministry of Agriculture) and high import duty on microbial technologies	SynCom's import and commercialization face significant regulatory and tax barriers; local production is necessary but still underdeveloped.	(Brazil – Import Tariffs 2023)
Developing countries	Weak policy frameworks and fragmented biofertilizer regulations	Developing Southeast Asian countries often do not have clear regulatory paths for synthetic microbes; they are frequently categorized with generic biofertilizers, which lack quality oversight.	(Ludher, 2023)

Table 5
A comparative evaluation of functional, environmental, and economic perspectives of cost-effective SynComs versus conventional agricultural inputs

Parameter	SynComs (if cost-effective)	Conventional Inputs
Nutrient efficiency	Multifunctional (N-fixation, P-solubilizing)	Single-function (e.g., urea)
Environmental impact	Low (biodegradable, non-toxic)	High (pollution, residue accumulation)
Long-term soil health	Improved (microbial diversity support)	Degraded (chemical overload)
Application frequency	Reduced (due to persistence)	Repeated applications needed
Market appeal	Sustainable/organic-friendly	Limited in organic markets
Upfront cost (initially)	Higher (R&D, formulation)	Lower (mass production scale)
Overall ROI (with adoption)	Competitive to superior	Stable

economic aspects of cost-effective SynComs with traditional agricultural inputs. Safety concerns and evolving regulatory frameworks also present obstacles. Developing effective SynComs requires a deep understanding of microbial ecology, plant-microbe interactions, systems biology, and significant research and development to optimize them for specific crops and environments.

10. Risk assessment and limitations of SynCom applications in sustainable agriculture

SynComs are designed to provide potential advantages for tackling agricultural challenges and enhancing sustainable agriculture. Nevertheless, their application may also lead to unintended negative effects. These effects can diminish the diversity of native microbial populations, resulting in shifts in community structure that could impact the overall functionality of the soil ecosystem (Timofeeva et al., 2023; Hao et al., 2023). Furthermore, SynComs may include strains that produce inhibitory substances, which can adversely affect other community members, even if such antagonism is unintentional (Wang et al., 2022). Similarly, the introduced SynCom can appear as the dominant strain within the microbial community, potentially disrupting the balance and function of the ecosystem (Dobrzyński et al., 2025; Afanador-Barajas et al., 2021). Changes in microbial community structure can influence the efficiency of nutrient cycling, thereby affecting plant nutrient uptake and overall soil health (Korneykova et al., 2024).

Moreover, certain native microbes play a vital role in suppressing pathogens; if SynCom outcompetes these beneficial microbes, it could undermine the soil's ability to control diseases. While some SynComs might initially succeed after inoculation, their populations could decrease over time due to resource insufficiency or interactions with the native community. Although SynComs can potentially suppress pathogens, they also pose the risk of introducing new or amplified pathogens that could adversely affect plant health and crop yields.

Consequently, the prevailing understanding is that SynComs require attentive design and rigorous testing to ensure they foster beneficial microbial interactions, enhance plant health, and mitigate potential risks. Researchers should concentrate on evaluating the performance of SynComs across varying field conditions, including different soil types, climates, and crop varieties. Continuous monitoring and assessment of SynCom applications are essential for identifying unexpected adverse effects and adapting strategies. Further research is necessary to elucidate the complex interactions among SynComs, indigenous microbes, and plants within the rhizosphere.

11. Conclusions

Synthetic microbial communities (SynComs) are artificially assembled microbe consortia that present a promising pathway toward sustainable agriculture, especially in escalating global challenges such as climate change, land degradation, and excessive reliance on chemical inputs. By enhancing plant health, improving nutrient cycling, and increasing resilience to environmental stresses, SynComs serve as a viable alternative to conventional agricultural methods. In addition to their function as biofertilizers, SynComs play a role in bioremediation and the valorization of agricultural residues, thereby supporting circular bioeconomy models. Integrating these communities into farming systems can help restore ecological balance, ensure long-term food security, and maintain soil and environmental health. To fully leverage their potential, however, advancing interdisciplinary research, implementing supportive policies, and encouraging farmer participation through knowledge transfer and collaborative innovation is crucial.

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Conflict of interest

The author declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author Contributions

Chanchao Chem – Conceptualization, Methodology, Investigation, Data Curation, Visualization, Writing – Original Draft, Writing – Review & Editing. **Tsukasa Ito** – Conceptualization, Funding Acquisition, Resources, Supervision, Writing – Review & Editing.

References

Abraham, J., Silambarasan, S., Logeswari, P., 2014. Simultaneous degradation of organophosphorus and organochlorine pesticides by bacterial consortium. Journal of the Taiwan Institute of Chemical Engineers 45 (5), 2590–2596. https://doi.org/10.1016/j.jtice.2014.06.014

Afanador-Barajas, L.N., Navarro-Noya, Y.E., Luna-Guido, M.L., Dendooven, L., 2021. Impact of a bacterial consortium on the soil bacterial community structure and maize (*Zea mays* L.) cultivation. Scientific Reports 11(1), 13092. https://doi.org/10.1038/s41598-021-92517-0

Al-Dhabi, N.A., Esmail, G.A., Mohammed Ghilan, A.K., Valan Arasu, M., 2019. Composting of vegetable waste using microbial consortium and biocontrol efficacy of *Streptomyces* Sp. Al-Dhabi 30 isolated from the Saudi Arabian environment for sustainable agriculture. Sustainability 11(23), 6845. https://doi.org/10.3390/su11236845

Alengebawy, A., Abdelkhalek, S.T., Qureshi, S.R., Wang, M.Q., 2021. Heavy metals and pesticides toxicity in agricultural soil and plants: Ecological risks and human health implications. Toxics 9(3), 42. https://doi.org/10.3390/toxics9030042

Alneyadi, A.H., Rauf, M.A., Ashraf, S.S., 2018. Oxidoreductases for the remediation of organic pollutants in water–a critical review. Critical reviews in biotechnology 38(7), 971–988. https://doi.org/10.1080/07388551.2017.1423275

Anisha, A.P., Pooja, S.S., 2023. A Study of Farmers Awareness Towards Biofertilizers Consumption in Karad District. Journal of Emerging Technologies and Innovative Research 10(12), 792–796.

Aswathi, A., Pandey, A., Sukumaran, R.K., 2019. Rapid degradation of the organophosphate pesticide–Chlorpyrifos by a novel strain of *Pseudomonas nitroreducens* AR-3. Bioresource technology 292, 122025. https://doi.org/10.1016/j.biortech.2019.122025

Bakki, M., Banane, B., Marhane, O., Esmaeel, Q., Hatimi, A., Barka, E.A., Bouizgarne, B., 2024. Phosphate solubilizing *Pseudomonas* and *Bacillus* combined with rock phosphates promoting tomato growth and reducing bacterial canker disease. Frontiers in Microbiology 15, 1289466. https://doi.org/10.3389/fmicb.2024.1289466

Baranek, J., Pluskota, M., Rusin, M., Konecka, E., Kaznowski, A., Wiland-Szymańska, J., 2023. Insecticidal activity of *Bacillus thuringiensis* strains isolated from tropical greenhouses towards *Cydia pomonella* and *Spodoptera exigua* larvae. BioControl 68(1), 39–48. https://doi.org/10.1007/s10526-022-10173-3

Batista, B.D., Singh, B.K., 2021. Realities and hopes in the application of microbial tools in agriculture. Microbial Biotechnology 14(4), 1258–1268. https://doi.org/10.1111/1751-7915.13866

Baweja, P., Kumar, S., Kumar, G., 2020. Fertilizers and pesticides: Their impact on soil health and environment. Soil health 59, 265–285. https://doi.org/10.1007/978-3-030-44364-1_15

Bhatt, P., Zhou, X., Huang, Y., Zhang, W., Chen, S., 2021. Characterization of the role of esterases in the biodegradation of organophosphate, carbamate, and pyrethroid pesticides. Journal of Hazardous Materials 411, 125026. https://doi.org/10.1016/j.jhazmat.2020.125026

Bonaterra, A., Badosa, E., Daranas, N., Francés, J., Roselló, G., Montesinos, E., 2022. Bacteria as biological control agents of plant diseases. Microorganisms 10(9), 1759. https://doi.org/10.3390/microorganisms10091759

Brazil – Import Tariffs. (2023, December 4). https://www.trade.gov/country-commercial-guides/brazil-import-tariffs

Brooks, S.M., Alper, H.S., 2021. Applications, challenges, and needs for employing synthetic biology beyond the lab. Nature Communications 12(1), 1390. https://doi.org/10.1038/s41467-021-21740-0

Burman, E., Bengtsson-Palme, J., 2021. Microbial community interactions are sensitive to small changes in temperature. Frontiers in Microbiology 12, 672910. https://doi.org/10.3389/fmicb.2021.672910

Buryska, T., Babkova, P., Vavra, O., Damborsky, J., Prokop, Z., 2018. A haloalkane dehalogenase from a marine microbial consortium possessing exceptionally broad substrate specificity. Applied and Environmental Microbiology 84(2), e01684-17. https://doi.org/10.1128/AEM.01684-17

Buta, M., Hubeny, J., Zieliński, W., Harnisz, M., Korzeniewska, E., 2021. Sewage sludge in agriculture–the effects of selected chemical pollutants and emerging genetic resistance determinants on the quality of soil and crops–a review. Ecotoxicology and Environmental Safety 214, 112070. https://doi.org/10.1016/j.ecoenv.2021.112070

Cao, T., Luo, Y., Shi, M., Tian, X., Kuzyakov, Y., 2023. Microbial interactions for nutrient acquisition in soil: Miners, scavengers, and carriers. Soil Biology and Biochemistry 109215. https://doi.org/10.1016/j.soilbio.2023.109215

Cappelli, S.L., Domeignoz-Horta, L.A., Loaiza, V., Laine, A.L., 2022. Plant biodiversity promotes sustainable agriculture directly and via belowground effects. Trends in Plant Science 27(7), 674–687. https://doi.org/10.1016/j.tplants.2022.02.003

Chaudhary, P., Xu, M., Ahamad, L., Chaudhary, A., Kumar, G., Adeleke, B.S., Abou Fayssal, S., 2023. Application of synthetic consortia for improvement of soil fertility, pollution remediation, and agricultural productivity: a review. Agronomy 13(3), 643. https://doi.org/10.3390/agronomy13030643

Cherif, H., Sghaier, I., Hassen, W., Amara, C., Masmoudi, A.S., Cherif, A., Neifar, M., 2022. *Halomonas desertis* G11, *Pseudomonas rhizophila* S211 and *Oceanobacillus iheyensis* E9 as biological control agents against wheat fungal pathogens: PGPB consorcia optimization through mixture design and response surface analysis. International Clinical Pathology Journal 9, 20–28. https://doi.org/10.15406/icpjl.2022.09.00204

Chiaranunt, P., 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

Das, R., Biswas, S., 2022. Influence of Abiotic Stresses on Seed Production and Quality. Seed Biology Updates, 1–25. http://dx.doi.org/10.5772/intechopen.106045

Dash, P.K., Padhy, S.R., Bhattacharyya, P., Pattanayak, A., Routray, S., Panneerselvam, P., Pathak, H., 2022. Efficient lignin decomposing microbial consortium to hasten rice-straw composting with moderate GHGs fluxes. Waste and Biomass Valorization 13(1), 481–496. https://doi.org/10.1007/s12649-021-01508-9

De Souza, R.S.C., Armanhi, J.S.L., Arruda, P., 2020. From microbiome to traits: designing synthetic microbial communities for improved crop resiliency. Frontiers in Plant Science 11, 553605. https://doi.org/10.3389/fpls.2020.01179

Delgado-Baquerizo, M., Singh, B.K., Liu, Y.R., Sáez-Sandino, T., Coleine, C., Muńoz-Rojas, M., Trivedi, P., 2025. Integrating ecological and evolutionary frameworks for SynCom success. New Phytologist. https://doi.org/10.1111/nph.70112

De-Lin, L., Huang, S.Y., Ma, C.Y., Zhang, X.Y., Sun, K., Zhang, W., Dai, C., 2024. Seed-borne bacterial synthetic community resists seed pathogenic fungi and promotes plant growth. Journal of Applied Microbiology lxae073. https://doi.org/10.1093/jambio/lxae073

Denaya, S., Yulianti, R., Pambudi, A., Effendi, Y., 2021. Novel microbial consortium formulation as plant growth promoting bacteria (PGPB) agent. Earth and Environmental Science 637(1), 012030. https://doi.org/10.1088/1755-1315/637/1/012030

Devi, A.R., Sharma, G.D., Majumdar, P.B., Pandey, P., 2018. A multispecies consortium of bacteria having plant growth promotion and antifungal activities, for the management of Fusarium wilt complex disease in potato (*Solanum tuberosum* L.). Biocatalysis and agricultural biotechnology 16, 614–624. https://doi.org/10.1016/j.bcab.2018.10.003

Devi, N.S.A., Balachandar, D., 2022. Synthetic Microbial Community (SynCom) for Sustainable Agriculture. Indian Journal of Plant Genetic Resources 35(03), 351–354. http://dx.doi.org/10.5958/0976-1926.2022.00098.5

Devi, R., Kaur, T., Kour, D., Yadav, A.N., 2022a. Microbial consortium of mineral solubilizing and nitrogen fixing bacteria for plant growth promotion of amaranth (*Amaranthus hypochondrius* L.). Biocatalysis and Agricultural Biotechnology 43, 102404. https://doi.org/10.1016/j.bcab.2022.102404

Devi, R., Kaur, T., Kour, D., Yadav, A.N., Suman, A., 2022b. Potential applications of mineral solubilizing rhizospheric and nitrogen fixing endophytic bacteria as microbial consortium for the growth promotion of chilli (*Capsicum annum* L.). Biologia 77(10), 2933–2943. https://doi.org/10.1007/s11756-022-01127-2

Dhankhar, N., Kumar, J., 2023. Impact of increasing pesticides and fertilizers on human health: A review. Materials Today: Proceedings. https://doi.org/10.1016/j.matpr.2023.03.766

Dobrzyński, J., Kulkova, I., Jakubowska, Z., Wróbel, B., 2025. Non-native PGPB consortium consisting of *Pseudomonas* sp. G31 and *Azotobacter* sp. PBC2 promoted winter wheat growth and slightly altered the native bacterial community. Scientific Reports 15(1), 3248. https://doi.org/10.1038/s41598-025-86820-3

Drepper, T., Eggert, T., Circolone, F., Heck, A., Krauss, U., Guterl, J.K., Jaeger, K.E., 2007. Reporter proteins for *in vivo* fluorescence without oxygen. Nature biotechnology 25(4), 443–445. https://doi.org/10.1038/nbt1293

Duarah, P., Haldar, D., Patel, A.K., Dong, C.D., Singhania, R.R., Purkait, M.K., 2022. A review on global perspectives of sustainable development in bioenergy generation. Bioresource Technology 348, 126791. https://doi.org/10.1016/j.biortech.2022.126791

El Chami, D., Daccache, A., El Moujabber, M., 2020. How can sustainable agriculture increase climate resilience? A systematic review. Sustainability 12(8), 3119. https://doi.org/10.3390/su12083119

El Hamss, H., Radouane, N., Belabess, Z., Lahlali, R., 2023. Microbial Consortia: An Approach to Enhance the Effectiveness of Beneficial Soil Microbes. In: Khan, M.R. (eds) Novel Biological and Biotechnological Applications in Plant Nematode Management. Springer, Singapore. (pp. 133–166). https://doi.org/10.1007/978-981-99-2893-4_6

Fang, L. (2018, March 8). Overview of biofertilizer registration in China. ChemLinked Agrochemical. https://agrochemical.chemlinked.com/agropedia/overview-biofertilizer-registration-china

Flores-Duarte, N.J., Navarro-Torre, S., Mateos-Naranjo, E., Redondo-Gómez, S., Pajuelo, E., Rodríguez-Llorente, I.D., 2023a. Nodule Synthetic Bacterial Community as Legume Biofertilizer under Abiotic Stress in Estuarine Soils. Plants 12(11), 2083. https://doi.org/10.3390/plants12112083

Flores-Duarte, N.J., Pajuelo, E., Mateos-Naranjo, E., Navarro-Torre, S., Rodríguez-Llorente, I. D., Redondo-Gómez, S., Carrasco López, J.A., 2023b. A Culturomics-Based Bacterial Synthetic Community for Improving Resilience towards Arsenic and Heavy Metals in the Nutraceutical Plant *Mesembryanthemum crystallinum*. International Journal of Molecular Sciences 24(8), 7003. https://doi.org/10.3390/ijms24087003

Frascella, A., Sarrocco, S., Lasinio, G.J., Pollice, A., Emiliani, G., Danti, R., Della Rocca, G., 2023. Characterization of *Trichoderma* species from forest ecosystems by high-throughput phenotypic microarray. Fungal Biology 127(10-11), 1376–1383. https://doi.org/10.1016/j.funbio.2023.09.004

Furukawa, K., 2018. Microbial degradation of polychlorinated biphenyls (PCBs). In Biodegradation and detoxification of environmental pollutants. CRC Press 33–58. https://doi.org/10.1201/9781351070201

Gonçalves, O.S., Creevey, C.J., Santana, M.F., 2023. Designing a synthetic microbial community through genome metabolic modeling to enhance plant–microbe interaction. Environmental microbiome 18(1), 81. https://doi.org/10.1186/s40793-023-00536-3

Goswami, S.K., Kashyap, P.L., Awasthi, S., 2019. Deciphering rhizosphere microbiome for the development of novel bacterial consortium and its evaluation for salt stress management in solanaceous crops in India. Indian Phytopathology 72, 479–488. https://doi.org/10.1007/s42360-019-00174-1

Gu, D., Andreev, K., Dupre, M.E., 2021. Major trends in population growth around the world. China CDC weekly 3(28), 604. https://doi.org/10.46234%2Fccdcw2021.160

Hadayat, A., Zahir, Z.A., Cai, P., Gao, C.H., 2024. Integrated application of synthetic community reduces consumption of herbicide in field Phalaris minor control. Soil Ecology Letters 6(2), 230207. https://doi.org/10.1007/s42832-023-0207-1

Hansen, M.L., Denes, Z., Jarmusch, S.A., Wibowo, M., Lozano-Andrade, C.N., Kovacs, A.T., Jelsbak, L., 2023. Resistance towards and biotransformation of Pseudomonas-produced secondary metabolites during community invasion. ISME Journal 2023-06. https://doi.org/10.1093/ismejo/wrae105

Hao, X., Wang, X., Chen, C., Liu, R., Yin, Y., Yao, J., Liu, X., 2023. Synthetic bacterial communities reshape microbial communities and enhance nutrient supply in desertified land of Northwest China. Applied Soil Ecology 189, 104972. https://doi.org/10.1016/j.apsoil.2023.104972

Huang, J., Zhao, X., Bürger, M., Chory, J., Wang, X., 2023. The role of ethylene in plant temperature stress response. Trends in plant science 28(7), 808–824. https://doi.org/10.1016/j.tplants.2023.03.001

Inda, M.E., Lu, T.K., 2020. Microbes as biosensors. Annual Review of Microbiology 74, 337–359. https://doi.org/10.1146/annurev-micro-022620-081059

Jankovska-Bortkevič, E., Katerova, Z., Todorova, D., Jankauskienë, J., Mockevičiűtë, R., Sergiev, I., Jurkonienë, S., 2023. Effects of auxin-type plant growth regulators and cold stress on the endogenous polyamines in pea plants. Horticulturae 9(2), 244. https://doi.org/10.3390/horticulturae9020244

Jensen, C.U., Rodriguez Guerrero, J.K., Karatzos, S., Olofsson, G., Iversen, S.B., 2017. Fundamentals of Hydrofaction™: Renewable crude oil from woody biomass. Biomass Conversion and Biorefinery 7(4), 495–509. https://doi.org/10.1007/s13399-017-0248-8

Jing, J., Garbeva, P., Raaijmakers, J.M., Medema, M.H., 2024. Strategies for tailoring functional microbial synthetic communities. The ISME Journal wrae049. https://doi.org/10.1093/ismejo/wrae049

Johns, N.I., Blazejewski, T., Gomes, A.L., Wang, H.H., 2016. Principles for designing synthetic microbial communities. Current Opinion in Microbiology 31, 146–153. https://doi.org/10.1016/j.mib.2016.03.010

Kabir, A.H., Baki, M.Z.I., Ahmed, B., Mostofa, M.G., 2024. Current, faltering, and future strategies for advancing microbiome-assisted sustainable agriculture and environmental resilience. New Crops 100013. https://doi.org/10.1016/j.ncrops.2024.100013

Karkaria, B.D., Fedorec, A.J., Barnes, C.P., 2021. Automated design of synthetic microbial communities. Nature communications 12(1), 672. https://doi.org/10.1038/s41467-020-20756-2

Kaur, S., Egidi, E., Qiu, Z., Macdonald, C.A., Verma, J.P., Trivedi, P., Singh, B.K., 2022. Synthetic community improves crop performance and alters rhizosphere microbial communities. Journal of Sustainable Agriculture and Environment 1(2), 118–131. https://doi.org/10.1002/sae2.12017

Kaur, T., Devi, R., Kumar, S., Sheikh, I., Kour, D., Yadav, A.N., 2022. Microbial consortium with nitrogen fixing and mineral solubilizing attributes for growth of barley (*Hordeum vulgare* L.). Heliyon 8(4). https://doi.org/10.1016/j.heliyon.2022.e09326

Kaur, T., Devi, R., Negi, R., Kumar, S., Singh, S., Rustagi, S., Yadav, A.N., 2024. Microbial consortium with multifunctional attributes for the plant growth of eggplant (*Solanum melongena* L.). Folia Microbiologica 1–12. https://doi.org/10.1007/s12223-024-0116

Khan, B.A., Nadeem, M.A., Nawaz, H., Amin, M.M., Abbasi, G.H., Nadeem, M., Ayub, M.A., 2023. Pesticides: impacts on agriculture productivity, environment, and management strategies. In Emerging Contaminants and Plants: Interactions, Adaptations and Remediation Technologies. Cham: Springer International Publishing. (pp. 109–134). https://doi.org/10.1007/978-3-031-22269-6_5

Khan, F., Siddique, A.B., Shabala, S., Zhou, M., Zhao, C., 2023. Phosphorus plays key roles in regulating plants' physiological responses to abiotic stresses. Plants 12(15), 2861. https://doi.org/10.3390/plants12152861

Khan, M.Y., Nadeem, S.M., Sohaib, M., Waqas, M.R., Alotaibi, F., Ali, L., Al-Barakah, F.N., 2022. Potential of plant growth promoting bacterial consortium for improving the growth and yield of wheat under saline conditions. Frontiers in microbiology 13, 958522. https://doi.org/10.3389/fmicb.2022.958522

Konecka, E., Baranek, J., Hrycak, A., Kaznowski, A., 2012. Insecticidal activity of *Bacillus thuringiensis* strains isolated from soil and water. The Scientific World Journal 2012. https://doi.org/10.1100/2012/710501

Korneykova, M., Vasenev, V., Kozlova, E., Soshina, A., Nikitin, D., Dolgikh, A., Saltan, N., 2024. Microbial communities of urban and industrial polluted soils in the Russian Arctic. Geoderma Regional 39, e00890. https://doi.org/10.1016/j.geodrs.2024.e00890

Kumar, A., Verma, J.P., 2019. The role of microbes to improve crop productivity and soil health. Ecological wisdom inspired restoration engineering 249–265. https://doi.org/10.1007/978-981-13-0149-0_14

Kumar, A., Maurya, B.R., Raghuwanshi, R., 2021. The microbial consortium of indigenous rhizobacteria improving plant health, yield and nutrient content in wheat (*Triticum aestivum*). Journal of Plant Nutrition 44(13), 1942–1956. https://doi.org/10.1080/01904167.2021.1884706

Kumar, P., Kumar, R., Thakur, K., Mahajan, D., Brar, B., Sharma, D., Sharma, A.K., 2023. Impact of pesticides application on aquatic ecosystem and biodiversity: a review. Biology Bulletin 50(6), 1362–1375. https://doi.org/10.1134/S1062359023601386

Lashani, E., Amoozegar, M.A., Turner, R.J., Moghimi, H., 2023. Use of Microbial consortia in bioremediation of metalloid polluted environments. Microorganisms 11(4), 891. https://doi.org/10.3390/microorganisms11040891

Li, X., Wu, S., Dong, Y., Fan, H., Bai, Z., Zhuang, X., 2021. Engineering microbial consortia towards bioremediation. Water 13(20), 2928. https://doi.org/10.3390/w13202928

Li, Y., Honda, K., 2021. Toward the development of defined microbial therapeutics. International immunology 33(12), 761–766. https://doi.org/10.1093/intimm/dxab038

Lin, H.H., Torres, M., Adams, C.A., Andeer, P.F., Owens, T.K., Zhalnina, K., Mortimer, J.C., 2024. Impact of inoculation practices on microbiota assembly and community stability in a fabricated ecosystem. Phytobiomes Journal, PBIOMES-06. https://doi.org/10.1094/PBIOMES-06-23-0050-R

Lin, L., 2022. Bottom-up synthetic ecology study of microbial consortia to enhance lignocellulose bioconversion. Biotechnology for Biofuels and Bioproducts 15(1), 14. https://doi.org/10.1186/s13068-022-02113-1

Liu, C., Jiang, M., Yuan, M.M., Wang, E., Bai, Y., Crowther, T.W., Liang, Y., 2023. Root microbiota confers rice resistance to aluminium toxicity and phosphorus deficiency in acidic soils. Nature Food 4(10), 912–924. https://doi.org/10.1038/s43016-023-00848-0

Liu, H., Qiu, Z., Ye, J., Verma, J.P., Li, J., Singh, B.K., 2022. Effective colonisation by a bacterial synthetic community promotes plant growth and alters soil microbial community. Journal of Sustainable Agriculture and Environment 1(1), 30–42. https://doi.org/10.1002/sae2.12008

Lü, H., Wei, J.L., Tang, G.X., Chen, Y.S., Huang, Y. H., Hu, R., Li, Q.X., 2024. Microbial consortium degrading of organic pollutants: Source, degradation efficiency, pathway, mechanism and application. Journal of Cleaner Production 141913. https://doi.org/10.1016/j.jclepro.2024.141913

Ludher, E.K. (2023, April 14). Fertiliser Security for Food Security in Southeast Asia: Going Local and Circular. Fulcrum. https://fulcrum.sg/fertiliser-security-for-food-security-in-southeast-asia-going-local-and-circular/

Lyu, H., Li, Y., Yu, A., 2024. Drive soil nitrogen transformation and improve crop nitrogen absorption and utilization-a review of green manure applications. Frontiers in Plant Science 14, 1305600. https://doi.org/10.3389/fpls.2023.1305600

Ma, C.Y., Zhang, W., Luo, D.L., Jiang, H.J., Wu, X.H., Sun, K., Dai, C.C., 2023. Fungal endophyte promotes plant growth and disease resistance of *Arachis hypogaea* L. by reshaping the core root microbiome under monocropping conditions. Microbiological Research 277, 127491. https://doi.org/10.1016/j.micres.2023.127491

Mącik, M., Gryta, A., Frąc, M., 2020. Biofertilizers in agriculture: An overview on concepts, strategies and effects on soil microorganisms. Advances in Agronomy 162, 31–87. https://doi.org/10.1016/bs.agron.2020.02.001

Mahmoud, G.AE., 2021. Biotic Stress to Legumes: Fungal Diseases as Major Biotic Stress Factor. In: Guleria, P., Kumar, V., Lichtfouse, E. (eds) Sustainable Agriculture Reviews 51. Sustainable Agriculture Reviews, Vol 51. Springer, Cham. https://doi.org/10.1007/978-3-030-68828-8_7

Maiyappan, S., Amalraj, E.L.D., Santhosh, A., Peter, A.J., 2010. Isolation, evaluation and formulation of selected microbial consortia for sustainable agriculture. Journal of Biofertilizers & Biopesticides 2(109), 2. https://doi.org/10.4172/2155-6202.1000109

Malik, S., Dhasmana, A., Kishore, S., Kumari, M., 2022. Microbes and microbial enzymes for degradation of pesticides. In Bioremediation and Phytoremediation Technologies in Sustainable Soil Management. Apple Academic Press. (pp. 95–127). https://doi.org/10.1201/9781003281207

Marín, O., González, B., Poupin, M.J., 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. https://doi.org/10.3389/fpls.2021.650609

Meena, M., Yadav, G., Sonigra, P., Nagda, A., Mehta, T., Swapnil, P., Zehra, A., 2023. Advantageous features of plant growth-promoting microorganisms to improve plant growth in difficult conditions. *I*n Plant-Microbe Interaction-Recent Advances in Molecular and Biochemical Approaches. Academic Press. (pp. 279–296). https://doi.org/10.1016/B978-0-323-91876-3.00019-1

Mehlferber, E.C., Arnault, G., Joshi, B., Partida-Martinez, L.P., Patras, K.A., Simonin, M., Koskella, B., 2024. A cross-systems primer for synthetic microbial communities. Nature microbiology 9(11), 2765–2773. https://doi.org/10.1038/s41564-024-01827-2

Mir, M.I., Mukkamula, N., Kumar, B.K., Raghu, K., Parray, J.A., Khan, I., Babalola, O.O., 2024. Impact of microbial consortium of Rhizobium tropici and Rhizobium mayense on the growth of Phaseolus vulgaris L. South African Journal of Botany 168, 562–572. https://doi.org/10.1016/j.sajb.2024.04.004

Misra, S., Semwal, P., Pandey, D.D., Mishra, S.K., Chauhan, P.S., 2023. Siderophore-Producing *Spinacia oleracea* Bacterial Endophytes Enhance Nutrient Status and Vegetative Growth Under Iron-Deficit Conditions. Journal of Plant Growth Regulation 1–14. https://doi.org/10.1007/s00344-023-11185-8

Mitra, D., Mondal, R., Khoshru, B., Senapati, A., Radha, T.K., Mahakur, B., Mohapatra, P.K.D., 2022. Actinobacteria-enhanced plant growth, nutrient acquisition, and crop protection: Advances in soil, plant, and microbial multifactorial interactions. Pedosphere 32(1), 149–170. https://doi.org/10.1016/S1002-0160(21)60042-5

Mukherjee, A., Chouhan, G.K., Gaurav, A.K., Jaiswal, D.K., Verma, J.P., 2021. Development of indigenous microbial consortium for biocontrol management. In New and future developments in microbial biotechnology and bioengineering. Elsevier. (pp. 91–104). https://doi.org/10.1016/B978-0-444-64325-4.00009-2

Nargotra, P., Sharma, V., Lee, Y.C., Tsai, Y.H., Liu, Y.C., Shieh, C.J., Kuo, C.H., 2022. Microbial lignocellulolytic enzymes for the effective valorization of lignocellulosic biomass: a review. Catalysts 13(1), 83. https://doi.org/10.3390/catal13010083

Nawaz, M., Sun, J., Shabbir, S., Khattak, W.A., Ren, G., Nie, X., Sonne, C., 2023. A review of plants strategies to resist biotic and abiotic environmental stressors. Science of the Total Environment 165832. https://doi.org/10.1016/j.scitotenv.2023.165832

Nazarov, P.A., Baleev, D.N., Ivanova, M.I., Sokolova, L.M., Karakozova, M.V., 2020. Infectious plant diseases: Etiology, current status, problems and prospects in plant protection. Acta Naturae 12(3), 46. https://doi.org/10.32607%2Factanaturae.11026

Nie, M., Wu, C., Tang, Y., Shi, G., Wang, X., Hu, C., Zhao, X., 2023. Selenium and *Bacillus proteolyticus* SES synergistically enhanced ryegrass to remediate Cu–Cd–Cr contaminated soil. Environmental Pollution 323, 121272. https://doi.org/10.1016/j.envpol.2023.121272

Olanrewaju, O.S., Babalola, O.O., 2019. Bacterial consortium for improved maize (*Zea mays* L.) production. Microorganisms 7(11), 519. https://doi.org/10.3390/microorganisms7110519

Pahalvi, H.N., Rafiya, L., Rashid, S., Nisar, B., Kamili, A.N., 2021. Chemical Fertilizers and Their Impact on Soil Health. In: Dar, G.H., Bhat, R.A., Mehmood, M.A., Hakeem, K.R. (eds) Microbiota and Biofertilizers, Vol 2. Springer, Cham. https://doi.org/10.1007/978-3-030-61010-4_1

Palmieri, D., Vitullo, D., De Curtis, F., Lima, G., 2017. A microbial consortium in the rhizosphere as a new biocontrol approach against fusarium decline of chickpea. Plant and soil 412, 425–439. https://doi.org/10.1007/s11104-016-3080-1

Pathma, J., Kennedy, R.K., Bhushan, L.S., Shankar, B.K., Thakur, K., 2021. Microbial Biofertilizers and Biopesticides: Nature's Assets Fostering Sustainable Agriculture. In: Prasad, R., Kumar, V., Singh, J., Upadhyaya, C.P. (eds) Recent Developments in Microbial Technologies. Environmental and Microbial Biotechnology. Springer, Singapore. https://doi.org/10.1007/978-981-15-4439-2_2

Prigigallo, M.I., Gómez-Lama Cabanás, C., Mercado-Blanco, J., Bubici, G., 2022. Designing a synthetic microbial community devoted to biological control: The case study of Fusarium wilt of banana. Frontiers in Microbiology 13, 967885. https://doi.org/10.3389/fmicb.2022.967885

Qiao, R., Xu, M., Jiang, J., Song, Z., Wang, M., Yang, L., Mao, Z., 2024. Plant growth promotion and biocontrol properties of a synthetic community in the control of apple disease. BMC Plant Biology 24. https://doi: 10.1186/s12870-024-05253-8

Rashid, A., Schutte, B.J., Ulery, A., Deyholos, M.K., Sanogo, S., Lehnhoff, E.A., Beck, L., 2023. Heavy metal contamination in agricultural soil: environmental pollutants affecting crop health. Agronomy 13(6), 1521. https://doi.org/10.3390/agronomy13061521

Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003 (Text with EEA relevance). EUR-Lex. (2024, November 20). https://eur-lex.europa.eu/eli/reg/2019/1009/oj/eng

Ritonga, F.N., Zhou, D., Zhang, Y., Song, R., Li, C., Li, J., Gao, J., 2023. The roles of gibberellins in regulating leaf development. Plants 12(6), 1243. https://doi.org/10.3390/plants12061243

Rodrigues, L.C.C., Fortini, R.M., CR Neves, M., 2023. Impacts of the use of biological pest control on the technical efficiency of the Brazilian agricultural sector. International Journal of Environmental Science and Technology 20(1), 1–16. https://doi.org/10.1007/s13762-022-04032-y

Sabir, M.S., Shahzadi, F., Ali, F., Shakeela, Q., Niaz, Z., Ahmed, S., 2021. Comparative effect of fertilization practices on soil microbial diversity and activity: an overview. Current Microbiology 78, 3644–3655. https://doi.org/10.1007/s00284-021-02634-2

Sachs, A., Szmuszkovicz, K., Schneider, M., (2020, November 30). EPA Releases Updated Draft Guidance for Biostimulant Products. Beveridge & Diamond. https://www.bdlaw.com/publications/epa-releases-updated-draft-guidance-for-biostimulant-products/#:~:text=In%20an%20updated%20draft%20guidance,that%20are%20subject%20to%20regulation

Saha, L., Bauddh, K., 2020. Sustainable agricultural approaches for enhanced crop productivity, better soil health, and improved ecosystem services. Ecological and Practical Applications for Sustainable Agriculture 1–23. https://doi.org/10.1007/978-981-15-3372-3_1

Seenivasagan, R., Babalola, O.O., 2021. Utilization of microbial consortia as biofertilizers and biopesticides for the production of feasible agricultural product. Biology 10(11), 1111. https://doi.org/10.3390/biology10111111

Segarra-Medina, C., Alseekh, S., Fernie, A.R., Rambla, J.L., Pérez-Clemente, R.M., Gómez-Cádenas, A., Zandalinas, S.I., 2023. Abscisic acid promotes plant acclimation to the combination of salinity and high light stress. Plant Physiology and Biochemistry 203, 108008. https://doi.org/10.1016/j.plaphy.2023.108008

Shah, I.H., Jinhui, W., Li, X., Hameed, M.K., Manzoor, M.A., Li, P., Chang, L., 2024a. Exploring the role of nitrogen and potassium in photosynthesis implications for sugar: Accumulation and translocation in horticultural crops. Scientia Horticulturae 327, 112832. https://doi.org/10.1016/j.scienta.2023.112832

Shah, T., Khan, Z., Asad, M., D'amato, R., Alsahli, A.A., Ahmad, P., 2024. Synthetic bacterial community derived from *Astragalus mongholicus* and plant-plant interactions inhibit cadmium uptake by modulating gene expression, antioxidant system and carbohydrate metabolism under cadmium contaminated soil. Journal of Environmental Chemical Engineering 12(1), 111619. https://doi.org/10.1016/j.jece.2023.111619

Sharma, P., 2023. Biocontrol strategies–retrospect and prospects. Indian Phytopathology 76(1), 47–59. https://doi.org/10.1007/s42360-023-00601-4

Shayanthan, A., Ordońez, P.A.C., Oresnik, I.J., 2022. The role of synthetic microbial communities (SynCom) in sustainable agriculture. Frontiers in Agronomy 4, 58. https://doi.org/10.3389/fagro.2022.896307

Sherpa, M.T., Sharma, L., Bag, N., Das, S., 2021. Isolation, characterization, and evaluation of native rhizobacterial consortia developed from the rhizosphere of rice grown in organic state Sikkim, India, and their effect on plant growth. Frontiers in microbiology 12, 713660. https://doi.org/10.3389/fmicb.2021.713660

Shinwari, Z.K., Tanveer, F., Iqrar, I., 2019. Role of microbes in plant health, disease management, and abiotic stress management. Microbiome in Plant Health and Disease: Challenges and Opportunities 231–250. https://doi.org/10.1007/978-981-13-8495-0_11

Singh, A., Roychoudhury, A., 2023. Abscisic acid in plants under abiotic stress: Crosstalk with major phytohormones. Plant Cell Reports 42(6), 961–974. https://doi.org/10.1007/s00299-023-03013-w

Singha, L.P., Shukla, P., 2023. Microbiome engineering for bioremediation of emerging pollutants. Bioprocess and Biosystems Engineering 46(3), 323–339. https://doi.org/10.1007/s00449-022-02777-x

Snyder, L.D., Gómez, M.I., Power, A.G., 2020. Crop varietal mixtures as a strategy to support insect pest control, yield, economic, and nutritional services. Frontiers in Sustainable Food Systems 4, 60. https://doi.org/10.3389/fsufs.2020.00060

Sotelo-Aguilar, J., Rios-Galicia, B., Mercado-Flores, Y., Arteaga-Garibay, R., Villa-Tanaca, L., Hernández-Rodríguez, C., 2023. Promotion of the growth and yield of *Zea mays* by synthetic microbial communities from Jala maize. Frontiers in Microbiology 14. https://doi.org/10.3389/fmicb.2023.1167839

Spescha, A., Weibel, J., Wyser, L., Brunner, M., Hermida, M.H., Moix, A., Maurhofer, M., 2023. Combining entomopathogenic *Pseudomonas* bacteria, nematodes and fungi for biological control of a belowground insect pest. Agriculture, Ecosystems & Environment 348, 108414. https://doi.org/10.1016/j.agee.2023.108414

Srivastava, S., Sharma, S., 2022. Metabolomic insight into the synergistic mechanism of action of a bacterial consortium in plant growth promotion. Journal of bioscience and bioengineering 134(5), 399–406. https://doi.org/10.1016/j.jbiosc.2022.07.013

Svolacchia, N., Sabatini, S., 2023. Cytokinins. Current Biology 33(1), 10–13. https://doi.org/10.1016/j.cub.2022.11.022

Tan, S. Q., Yin, Y., Cao, K.L., Zhao, X.X., Wang, X.Y., Zhang, Y.X., Shi, W.P., 2021. Effects of a combined infection with *Paranosema locustae* and *Beauveria bassiana* on *Locusta migratoria* and its gut microflora. Insect Science 28(2), 347–354. https://doi.org/10.1111/1744-7917.12776

Tariq, A., Guo, S., Farhat, F., Shen, X., 2025. Engineering Synthetic Microbial Communities: Diversity and Applications in Soil for Plant Resilience. Agronomy 15(3), 513. https://doi.org/10.3390/agronomy15030513

Thakur, N., Kaur, S., Tomar, P., Thakur, S., Yadav, A.N., 2020. Microbial biopesticides: current status and advancement for sustainable agriculture and environment. In New and future developments in microbial biotechnology and bioengineering. Elsevier. (pp. 243–282). https://doi.org/10.1016/B978-0-12-820526-6.00016-6

Tian, Z., Wang, J.W., Li, J., Han, B., 2021. Designing future crops: challenges and strategies for sustainable agriculture. The Plant Journal 105(5), 1165–1178. https://doi.org/10.1111/tpj.15107

Timofeeva, A.M., Galyamova, M.R., Sedykh, S.E., 2023. Plant growth-promoting bacteria of soil: designing of consortia beneficial for crop production. Microorganisms 11(12), 2864. https://doi.org/10.3390/microorganisms11122864

Tripathi, R., Tewari, R., Singh, K.P., Keswani, C., Minkina, T., Srivastava, A.K., Sansinenea, E., 2022. Plant mineral nutrition and disease resistance: A significant linkage for sustainable crop protection. Frontiers in Plant science 13, 883970. https://doi.org/10.3389/fpls.2022.883970

Tsolakidou, M.D., Stringlis, I.A., Fanega-Sleziak, N., Papageorgiou, S., Tsalakou, A., Pantelides, I.S., 2019. Rhizosphere-enriched microbes as a pool to design synthetic communities for reproducible beneficial outputs. FEMS Microbiology Ecology 95(10), fiz138. https://doi.org/10.1093/femsec/fiz138

Valle-García, J.D., Ali, A., Patra, J.K., Kerry, R.G., Das, G., Fernández-Luqueńo, F., 2023. Integration of Eco-Friendly Biological and Nanotechnological Strategies for Better Agriculture: A Sustainable Approach. Agricultural and Environmental Nanotechnology: Novel Technologies and their Ecological Impact 647-674. https://doi.org/10.1007/978-981-19-5454-2_24

Vega-Celedón, P., Bravo, G., Velásquez, A., Cid, F.P., Valenzuela, M., Ramírez, I., Seeger, M., 2021. Microbial diversity of psychrotolerant bacteria isolated from wild flora of andes mountains and patagonia of chile towards the selection of plant growth-promoting bacterial consortia to alleviate cold stress in plants. Microorganisms 9(3), 538. https://doi.org/10.3390/microorganisms9030538

Verma, J.P., Jaiswal, D.K., Krishna, R., Prakash, S., Yadav, J., Singh, V., 2018. Characterization and screening of thermophilic *Bacillus* strains for developing plant growth promoting consortium from hot spring of Leh and Ladakh region of India. Frontiers in Microbiology 9, 1293. https://doi.org/10.3389/fmicb.2018.01293

Wang, H., Liu, R., You, M.P., Barbetti, M.J., Chen, Y., 2021. Pathogen biocontrol using plant growth-promoting bacteria (PGPR): Role of bacterial diversity. Microorganisms 9(9), 1988. https://doi.org/10.3390/microorganisms9091988

Wang, S., Dai, G., Yang, H., Luo, Z., 2017. Lignocellulosic biomass pyrolysis mechanism: A state-of-the-art review. Progress in energy and combustion science 62, 33–86. https://doi.org/10.1016/j.pecs.2017.05.004

Wang, Y., Liu, H., Shen, Z., Miao, Y., Wang, J., Jiang, X., Li, R., 2022. Richness and antagonistic effects co-affect plant growth promotion by synthetic microbial consortia. Applied Soil Ecology 170, 104300. https://doi.org/10.1016/j.apsoil.2021.104300

Yan, W., Liu, Y., Malacrinň, A., Zhang, J., Cheng, X., Rensing, C., Wu, H., 2024. Combination of biochar and PGPBs amendment suppresses soilborne pathogens by modifying plant-associated microbiome. Applied Soil Ecology 193, 105162. https://doi.org/10.1016/j.apsoil.2023.105162

Yin, C., Hagerty, C.H., Paulitz, T.C., 2022. Synthetic microbial consortia derived from rhizosphere soil protect wheat against a soilborne fungal pathogen. Frontiers in Microbiology 13, 908981. https://doi.org/10.3389/fmicb.2022.908981

Yokoyama, T., 2023. Development and Use of Biofertilizers in Japan: Current Situation and Future Directions. Asia-Pacific Biofertilizers and Biopesticides Information Platform. 1–12. https://doi.org/10.56669/TGJS1978

Zandalinas, S.I., Sengupta, S., Fritschi, F.B., Azad, R.K., Nechushtai, R., Mittler, R., 2021. The impact of multifactorial stress combination on plant growth and survival. New Phytologist 230(3), 1034–1048. https://doi.org/10.1111/nph.17232

Zhang, B., Liu, D., Liu, H., Shen, J., Zhang, J., He, L., Shi, K., 2024. Impact of indigenous *Oenococcus oeni* and *Lactiplantibacillus plantarum* species co-culture during Cabernet Sauvignon wine malolactic fermentation: Kinetic parameters, color and aroma. Food Chemistry: X 101369. https://doi.org/10.1016/j.fochx.2024.101369

Zhang, J., Liu, Y.X., Zhang, N., Hu, B., Jin, T., Xu, H., Bai, Y., 2019. NRT1.1B is associated with root microbiota composition and nitrogen use in field-grown rice. Nature biotechnology 37(6), 676–684. https://doi.org/10.1038/s41587-019-0104-4

Zhang, Y., Ye, C., Su, Y., Peng, W., Lu, R., Liu, Y., Zhu, S., 2022. Soil Acidification caused by excessive application of nitrogen fertilizer aggravates soil-borne diseases: Evidence from literature review and field trials. Agriculture, Ecosystems & Environment 340, 108176. https://doi.org/10.1016/j.agee.2022.108176

Zheng, G., Yin, T., Lu, Z., Boboua, S., Li, J., Zhou, W., 2020. Degradation of rice straw at low temperature using a novel microbial consortium LTF-27 with efficient ability. Bioresource technology 304, 123064. https://doi.org/10.1016/j.biortech.2020.123064

Zheng, X., Zhang, Y., Zhang, Y., Cui, Y., Wu, J., Zhang, W., Zou, J., 2023. Interactions between nitrogen and phosphorus in modulating soil respiration: A meta-analysis. Science of The Total Environment 905, 167346. https://doi.org/10.1016/j.scitotenv.2023.167346

Zhou, J., Liu, Y., Xu, W., Wang, Z., Chen, W., Hu, Y., 2024. Effect of synthetic microbial communities on rhizosphere and root-endophytic microbiota of soybean[J]. Chinese Journal of Eco-Agriculture 32(4), 571–581. https://doi.org/10.12357/cjea.20230496

Zhou, X., Zhou, X., Wang, C., Zhou, H., 2023. Environmental and human health impacts of volatile organic compounds: A perspective review. Chemosphere 313, 137489. https://doi.org/10.1016/j.chemosphere.2022.137489

Zhuang, L., Li, Y., Wang, Z., Yu, Y., Zhang, N., Yang, C., Wang, Q., 2021. Synthetic community with six *Pseudomonas* strains screened from garlic rhizosphere microbiome promotes plant growth. Microbial Biotechnology 14(2), 488–502. https://doi.org/10.1111/1751-7915.13640