PLANT SCIENCE TODAY
Vol x(x): xx–xx
https://doi.org/10.14719/pst.9509

eISSN 2348-1900

REVIEW ARTICLE

Bioinoculants: A natural boost for tuber yields

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Received: 19 May 2025; Accepted: 11 August 2025; Available online: Version 1.0: 18 September 2025

Cite this article: Vaishnavi KV, Shoba TK, Thangamani C, Malathi P, Anandham R, Balachandar D, Sakthivel N, Kavitha C, Raghu R. Bioinoculants: A natural boost for tuber yields. Plant Science Today (Early Access). https:/doi.org/10.14719/pst.9509

Abstract

Tuber crops play a pivotal role in global food systems. However, their productivity is often constrained by declining soil fertility, pest and disease pressures and over reliance on chemical inputs. Bioinoculants offer sustainable solutions through enhanced nutrient availability, stress tolerance and disease resistance. This review examines the application, dosage and efficiency of bioinoculants in tuber crops. Strains such as *Azospirillum lipoferum* have been shown to increase potato tuber weight by 16-22.7 %, while co-inoculation with *Pseudomonas fluorescens* and *Burkholderia ambifaria* improved yield by up to 63.6 %. *Rhizophagus irregularis* and *Glomus mosseae* significantly enhanced nutrient uptake and yield, with an increase of up to 56 % in yams and over 18 % in sweet potato. Biocontrol agents like *Trichoderma harzianum* and *Streptomyces* spp. reduced disease incidence and improved tuber quality. In cassava, combining Oso Bio-Degrader (OBD) biofertilizer (4 t/ha) with NPK (300 kg/ha) resulted in a maximum yield of 31.2 t/ha. Sweet potato trials showed that using *Pseudomonas fluorescens* with reduced fertilizer inputs-maintained yields close to those under full NPK doses. Bioinoculants also improved tuber nutritional quality and reduced postharvest losses. Application methods such as seed coating, root dipping and incorporation into organic amendments enhanced efficacy and field performance. The findings highlight the significant potential of bioinoculants in boosting tuber crop productivity while reducing reliance on synthetic agrochemicals.

Keywords: biotic and abiotic stress; soil health; sustainable agriculture; yield efficiency

Introduction

Root and tuber crops are vital to the world's food supply, serving not only as a major source of human nutrition but also as an important component of feedstock for animals and starting substrate for varied industrial processes. By 2050, India's population is expected to reach 1.62 billion. Hence, the demand for cereals could rise to 345 million tons by 2030 and as high as 360 million tons by 2050 (1). The potential shortfall in meeting these demands may be mitigated by tubers as they are dense in energy and offer high yields. These crops are well-suited to withstand the effects of climate change, performing well under biotic and abiotic stress conditions (1). Additionally, they have versatile industrial applications, notable nutritional benefits and a remarkable capacity for carbon fixation. Globally, tubers like sweet potato and cassava are the most important food crops in developing countries based on annual production volumes (1). The cultivated area of tuber crops accounts for 67 million hectares worldwide, yielding 887 million tonnes, with a productivity of 11 t/ha. Among these tuber crops, cassava is the most significant tropical tuber crop, a staple food in many African nations. Potatoes account for around 44 % of the total root and tuber production, followed by cassava (32.91 %), sweet potatoes (12.72 %), yams (8.23 %) and aroids (2.4 %). While potatoes lead in overall production, cassava covers the largest cultivation area. In terms of productivity, potatoes and sweet potatoes stand out, yielding 20.1 tons per hectare and 12.26 tons per hectare, respectively (2).

Ensuring sustainable agriculture is vital for maintaining high levels of food production, unsustainable resource use not only degrades agro-ecological systems but also diminishes the economic viability of agriculture. Among all agricultural resources, soil is of paramount importance and maintaining its fertility is key for achieving high productivity (3). To sustain soil health, it is crucial to manage soil resources carefully by minimizing pollution, preventing excessive nutrient depletion and maintaining organic carbon levels. While chemical fertilisers have successfully increased crop yields, integrating them with bio inoculants and organic manures helps to improve the soil health, enhances the nutrient use efficiency and addresses issues caused by excessive fertiliser use (3).

The misuse of chemical fertilisers severely affects the microbiome of the soil, leading to accumulation of hazardous metals like chromium, nickel, etc., thereby leading to biomagnification (4, 5). This emphasises the need for careful management of fertilisers to avoid environmental and health risks, which can be mitigated by using bioinoculants. In organic farming systems, it is difficult to meet the nutrient requirement as organic fertilisers function as slow-release fertilisers and hence cannot meet the immediate demands of the crop. Therefore, chemical fertilisers along with organic fertilisers are often recommended to improve crop yields in organic farming systems (6, 7).

This review emphasises the importance of both tuber crops and bioinoculants in addressing future food security challenges while promoting sustainable farming practices. It aims to explore the role of bioinoculants in promoting sustainable agriculture through their integration with chemical and organic fertilisers, with a focus on improving soil health, enhancing nutrient use efficiency and reducing the adverse impacts of chemical inputs. It further discusses the potential of tuber crops as a key component in achieving food security under ecologically sustainable farming systems.

This review is based on a comprehensive analysis of peer-reviewed research articles, reviews, books and reports published between 1990 and 2025. Literature was retrieved from reputable scientific databases including Scopus**,** Web of Science, PubMed and Google Scholar using keywords such as “bioinoculants”, “sustainable agriculture”, “soil health”, “chemical fertilisers”, “organic manures” and “tuber crops”. Articles included in the review were selected based on their relevance to the integration of bioinoculants with chemical and organic fertilisers, their effects on soil microbiome, nutrient cycling and productivity in sustainable agricultural systems. Studies not directly related to agricultural soil management or those focusing solely on non-edible crops were excluded. The information was synthesized qualitatively to identify patterns, emerging trends, knowledge gaps and the potential synergistic effects of combining fertiliser sources in tuber crop-based systems.

Bioinoculants

Bioinoculants are preparations containing one or more strains of beneficial microorganisms that colonise the rhizosphere or the interior of the plant and promote growth through increased supply or availability of primary nutrients to the host plant (8, 9). They comprise of microbes that are crucial in enhancing sustainable farming as they improve soil health, plant growth and offer protection against pathogens and pests. Their mechanisms of action affect various stages of plant growth, including soil, plant development and post-harvest processes. They enhance soil fertility and crop yield by converting nutrients from an unavailable form to an available form, primarily by stimulating microbial populations in the soil. These microbes are essential for nutrient solubilisation and nitrogen fixation, which are directly responsible for the healthy growth of plants. Additionally, biofertilizers suppress diseases, break down contaminants and produce growth-stimulating substances like auxins and cytokinins. They also enhance plant resilience to harsh weather conditions and hence, can be used as biofertilizers, biocontrol agents/biopesticides (Table 1) (10, 11).

Table 1. Microbial effects on tuber crops

Microorganism	Effect/Action in Tuber	Tuber Type	Reference
Acinetobacter rudis	Improved tuber size, phosphorus uptake, early growth	Potato	(30)
Aspergillus niger	Broad-spectrum suppression of fungal pathogens; reduced lesion size and decay severity	Potato	(63), (64), (65); (66)
Azospirillum lipoferum	Nitrogen fixation, mineral uptake, siderophore production, phytohormone synthesis, induced resistance to blight, improved yield and root architecture	Potato; Sweet Potato	(13); (14); (16); (17)
Bacillus megaterium P68	Yield boost, vitamin C, protein, starch accumulation, enhanced NPK uptake	Potato	(32)
Bacillus spp. (*B. subtilis*, *B. amyloliquefaciens*, *B. sp. K9*)	Suppression of *Rhizoctonia solani* and *Streptomyces scabies*, improved yield and plant physiology	Potato; Sweet Potato	(55, (56); (42)
Bacillus subtilis	Reduced PVY severity, hypersensitive response	Potato	(58)
Bacillus subtilis (strain 10-4) + salicylic acid	Reduced late blight, improved nutritional quality	Potato	(57)
Bacillus velezensis, *B. safensis*	Controlled foot rot; increased tuber number and weight	Sweet Potato	(61); (62)
Burkholderia ambifaria, *Pseudomonas fluorescens*	Co-inoculation with *A. lipoferum* improved yield under continuous cropping systems	Potato	(14)
Genotype-specific PSB communities	Nitrogen fixation and phosphorus mineralization	Sweet Potato	(33)
Arbuscular Mycorrhizal Fungi (AMF)	Phosphorus uptake, increased yield, stress resilience, metabolite enhancement, systemic resistance, gene regulation	Potato; Yam; Sweet Potato	(18), (20), (21), (22), (23), (24), (25), (27), (28)
Enterobacter cloacae, *Bacillus thuringiensis*, *Pseudomonas pseudoalcaligenes*	Solubilized phosphorus; increased shoot P and biomass	Potato	(31)
Pseudomonas spp. (*P. fluorescens*, *P. resinovorans*)	Disease suppression, phosphorus solubilization, systemic resistance, genotype-specific enrichment	Potato; Sweet Potato	(45), (46), (47), (48), (49), (50), (51), (52), (53)
Streptomyces A1RT	Suppression of common scab; increased IAA and antibiotic production	Potato	(34)
Streptomyces lavendulae SPS-33	VOC-mediated suppression of postharvest black-spot decay	Sweet Potato	(37)
Streptomyces PBSH9	Suppression of common scab under field conditions	Potato	(35)
Streptomyces spp. (*S. netropsis*, *S. ambofaciens*, *S. actuosus*)	Antiviral resistance to PVY via PR-1b gene expression	Potato	(36)
Trichoderma spp.	Biocontrol, resistance enhancement, phosphate solubilization, improved tuber yield, postharvest rot suppression	Potato; Sweet Potato	(38), (39), (40), (41), (42), (43), (44)

For instance, *Azospirillum* species are known to enhance nitrogen fixation, mineral uptake and phytohormone production, improving root growth and nutrient absorption (12). Under conditions of iron deficiency, *Azospirillum lipoferum* produces siderophores that exhibit antimicrobial properties, offering protection against pathogens. It promotes plant growth through multiple mechanisms, including biological nitrogen fixation, improved mineral uptake and phytohormone production (auxins, gibberellins, cytokinins and polyamines), which enhance root development and nutrient acquisition (13). In potatoes, seed tuber treatment with *A. lipoferum* AL 3 has been shown to increase tuber weight by 16-22.7 % (14). When co-inoculated with *Pseudomonas fluorescens* and *Burkholderia ambifaria*, an increase in yield up to 63.6 % has been observed under continuous cropping systems. Foliar application of *A. lipoferum* AL 3 also resulted in a ~68 % reduction in early blight (*Alternaria solani*) severity by inducing systemic resistance i.e., elevated levels of peroxidase, polyphenol oxidase, phenylalanine ammonia lyase, salicylic acid, total phenolics and hydrogen peroxide (15). Inoculation with *A. lipoferum* has improved tuber number, fresh and dry weight, particularly in potato cultivars such as Agria, Caeser and Banba. Aeroponic and field trials have demonstrated enhanced stolon formation, mini-tuber production and dry matter accumulation, with cultivar-dependent responses (16). Similar benefits were observed in sweet potato (*Ipomoea batatas*), where *A. lipoferum* application improved tuber quality, protein content and phosphorus uptake while enhancing root structure, phosphorus absorption and rhizosphere conditions, even under reduced nitrogen fertiliser input (17).

Mycorrhizae having a symbiotic relationship between roots of higher plants and fungi, play a critical role in enhancing nutrient uptake. Arbuscular mycorrhizal fungi (AMF), for example, increase the plant's phosphorus intake by expanding the surface area for nutrient absorption, improving soil contact and altering the root environment. AM fungi can also help to control soil-borne pathogens and influence plant susceptibility to insect pests (18). The use of AMF has improved the organic matter and nutrient quality of the soil and thereby the soil ecosystem (19).

AMF form symbiotic associations with many tuber crops, significantly enhancing nutrient uptake, yield and stress resilience. In a field trial involving five commercial yam (*Dioscorea* spp.) varieties inoculated with six AMF strains (*Glomus clarum, G. etunicatum, G. fasciculatum, G. mosseae, Gigaspora* sp., *Acaulospora* sp.), root colonization ranged from 63 % to 90 %, with corresponding tuber yield increases of 20-56 %, depending on the AMF-host pairing. Additionally, AMF inoculation led to marked increases in secondary metabolites-including polyphenols, flavonoids and anthocyanins by up to 106 % in both tuber flesh and peel (20).

A large-scale field dataset spanning 231 trials across North America and Europe demonstrated that inoculation with *Rhizophagus irregularis* DAOM 197198 resulted in an average yield increase of 9.5 % (~3.9 t/ha), a statistically significant improvement ($P<0.0001$) (21). Similarly, a recent meta-analysis of 106 studies confirmed that AMF consistently enhanced yield and nutrient uptake in potatoes, although the effect on above ground biomass was less pronounced (22). Specific AMF species such as *R. intraradices*, *R. irregularis*, *G. mosseae* and *Gigaspora* spp. have been associated with improved plant growth, chlorophyll content and tuber yield. Moreover, these fungi contributed to reduced disease severity caused by pathogens like *Rhizoctonia solani* and *Phytophthora infestans* (23). At the molecular level, AMF symbiosis, particularly with *R. irregularis* induces changes in the expression of sugar transporter genes (e.g., *SWEET* genes) in potato roots, peaking around six weeks post-inoculation, suggesting active nutrient exchange during critical growth stages (24). Under abiotic stress conditions such as drought, AMF species like *Claroideoglomus lamellosum* have been shown to enhance the antioxidant varies responses of tubers. However, the degree of stress mitigation varied with both fungal strain and stress intensity (25).

Field trials in Uganda demonstrated that inoculation with AMF, combined with starter NPK fertilizer, significantly boosted root crop productivity. Yields increased from 4.5t/ha to over 30t/ha, although responses varied depending on soil type and seasonal conditions (26). In a controlled study in sweet potato, AMF inoculation led to marked improvement in vegetative and yield traits, including 29.7 % increase in vine length, 22.4 % in branch number, 28.7 % in shoot biomass and 18.3 % in storage root yield (27). Further pot experiments using *Funneliformis mosseae* and *Claroideoglomus etunicatum* confirmed that AMF enhances root architecture and nutrient uptake. Inoculated plants exhibited increased root branching, root hair density and total root surface area, resulting in improved absorption of nitrogen, phosphorus and potassium (28).

Essential nutrients like N, P, K and Fe are solubilised by phosphate solubilising bacteria (PSB) by producing organic acids. Some PSBs also act as mycorrhizal helper bacteria, forming synergistic relationships with mycorrhizae to better exploit phosphorus sources. *Sphingomonas, Streptomyces* and *Methylibium* are some of the bacterial genera that play various ecological roles and have significant biotechnological uses. *Sphingomonas*, commonly found in soil and aquatic environments, are recognised for their ability to break down compounds and their potential in bioremediation. *Streptomyces*, a prominent group of actinobacteria, are famous for their antibiotic production. *Methylibium*, which is sometimes categorised alongside *Streptomyces*, contributes to the degradation of specific organic materials. (29).

In *Lady Rosetta* potatoes, inoculation with *Acinetobacter rudis* significantly improved tuber size, weight and phosphorus content, as well as seed germination and early plant growth under field conditions (30). A PSB consortium derived from wild potato species-comprising *Enterobacter cloacae*, *Bacillus thuringiensis* and *Pseudomonas pseudoalcaligenes* effectively solubilized both inorganic (calcium phosphate) and organic (phytin) forms of phosphorus. This led to increased shoot phosphorus content and overall plant biomass in modern potato varieties (31). Field trials with *Bacillus megaterium* P 68 showed an improvement in yield of 3-19 % for small tubers and 9-17 % for marketable tubers. Additionally, this strain improved nutritional quality by increasing vitamin C (8-23 %), protein content (50-124 %), starch accumulation and NPK uptake, particularly phosphorus (14-27 %) and potassium (10-13 %) (32). Sweet potato rhizosphere harbours genotype-specific PSB communities, where wild sweet potato genotypes are particularly associated with nitrogen-fixing and phosphorus-mineralising bacteria (33).

Streptomyces species are widely recognised for their dual roles in promoting plant growth and suppressing plant diseases. A non-pathogenic strain, *Streptomyces* A1 RT, has shown strong biocontrol activity against common scab (*Streptomyces scabies*) while simultaneously enhancing plant growth. In greenhouse trials, A1 RT reduced disease severity from over 50 % to below 5 % and increased average tuber weight from ~40 g (in pathogen-only treatments) to ~60 g. This dual effect is attributed to its production of Indole-3-acetic acid (IAA; ~26 µg/mL) and antibiotic compounds such as isatropolone C, which promote growth and inhibit pathogens (34). *Streptomyces* sp. PBSH 9 has also demonstrated effective suppression of common scab under field conditions. Long-term studies across multiple locations showed significantly reduced disease symptoms and improved yields when potatoes were treated both in soil and on seed tubers (35). Beyond bacterial pathogens, *Streptomyces* spp. culture filtrates (e.g., from *S. netropsis*, *S. ambofaciens*, *S. actuosus*) have shown antiviral properties. Foliar applications induced systemic resistance against *Potato virus Y* (PVY), by reducing viral infection and increasing PR-1b gene expression (36). In sweet potato, *Streptomyces lavendulae* strain SPS-33, isolated from the rhizosphere, produces volatile organic compounds (VOCs) that effectively inhibit *Ceratocystis fimbriata*, the causal agent of post-harvest black-spot decay. This strain offers a promising biocontrol strategy to reduce post-harvest losses (37).

Biocontrol agents provide an eco-friendly alternative to chemical pesticides in managing crop diseases. They comprise of specific fungus or bacterium that antagonistically affect pathogens (38). One of the most effective biocontrol agents is the *Trichoderma* species, known for their antagonistic properties against soil and seed-borne fungal diseases in crops. The biocontrol mechanisms of *Trichoderma* include competition for substrate, colonization of the pathogen's ecological niche, antibiotic production and release of cell wall degrading enzymes (39). Besides controlling plant pathogens, *Trichoderma* strains promote root development, increase productivity, enhance resistance to harsh weather conditions and improve nutrient absorption (40). Additionally, they solubilise phosphates and micronutrients, helping plants establish deeper root systems and inducing drought resistance. Certain compounds produced by *Trichoderma* like trichothecin and trichodermin have antimicrobial effect on bacteria and fungi and also trigger plant defence mechanisms, increasing overall resistance (40).

Application of a *Trichoderma* based bioformulation significantly increased potato growth and productivity. There was more than a two fold increase in plant biomass, with fresh weight increasing by 107 % and dry weight by 74 %. Tuber yield rose by 36 % and tuber number increased by 41 % (41). A microbial consortium of *Trichoderma harzianum* and *Bacillus subtilis* effectively reduced the severity of common scab by 30-46 % and improved tuber yield by 23-32 % across two growing seasons (42). *Trichoderma viride* isolate Tvd 44 induced systemic resistance against *Potato Virus Y* (PVY), enhancing the activity of defence related enzymes (peroxidase, polyphenol oxidase), increasing total protein levels and improving chlorophyll content, which supports better photosynthesis and overall plant health (43). Several *Trichoderma* species, including *T. harzianum*, *T. viride*, *T. hamatum* and *T. pseudokoningii*, significantly reduced postharvest rot in sweet potato tubers by 47-69 % after four months of storage. These effects were largely attributed to the production of antifungal metabolites (44).

Pseudomonas species produce secondary metabolites like siderophores, hydrogen cyanide (HCN) and proteases that prevent infections. These metabolites exhibit antagonistic activity against pathogens, including *Phytophthora*, *Pythium*, *Fusarium* and *Rhizoctonia solani* (45). Especially in iron-deficient environments, *Pseudomonas* strains produce antibiotics like pyrolnitrin and pyoluteorin, which play a critical role in disease suppression (46). Moreover, they have been recognised for their ability to solubilise phosphorus, further contributing to nutrient availability for plants (47). They play a vital role in managing soil and tuber-borne diseases while enhancing growth in tuber crops like potato and sweet potato. In potato, *Pseudomonas* species suppress major pathogens such as *Rhizoctonia solani*, *Sclerotinia sclerotiorum*, *Sclerotium rolfsii*, *Fusarium* spp. and *Pectobacterium atrosepticum*. This biocontrol activity is mediated through the production of antibiotics such as 2, 4-diacetylphloroglucinol, phenazine-1-carboxylic acid and pyoverdine, siderophores and hydrolytic enzymes, along with the induction of systemic resistance in host plants (48, 49). Notably, strains of *P. fluorescens* reduce tuber peel contamination by 60-85 % by interfering with pathogen quorum sensing and occupying ecological niches (50). In addition, phenazine-producing strains of *Pseudomonas* show strong inhibition of *Phytophthora infestans in vitro*, with some isolates completely preventing lesion development (48). In sweet potato, treating cuttings with a *P. fluorescens* based biofertiliser significantly enhanced yield. A combined treatment (*P. fluorescens* + 50 % NPK) matched the yield of full NPK treatment (~49.6 t/ha vs. 51.6 t/ha) and outperformed controls (~56.1 t/ha with full NPK + *P. fluorescens*) (51). Rhizosphere studies show that *Pseudomonas* is preferentially enriched in starch-rich sweet potato genotypes, indicating genotype-specific recruitment of beneficial microbes (52). Furthermore, the inclusion of *Pseudomonas resinovorans* in microbial consortia led to substantial yield increases on sandy soils 1.5 to 1.9 times without fertilizer and 1.22 to 1.87 times with fertigation, demonstrating its effectiveness under low-input conditions (53).

Biopesticides represent an environmentally friendly alternative to chemical pesticides, providing a natural means of pest and pathogen control. These include products derived from natural organisms that combat various agricultural pests. By reducing the dependency on chemical pesticides, biopesticides promote ecological balance and long-term soil health. They use microorganisms as live ingredients each designed to target a particular pest. A notable example is *Bacillus thuringiensis* (Bt), a bacterium that produces a protein harmful to specific insects like those affecting cabbage and potatoes. Microbial pesticides, such as Bt, need regular monitoring such that they only harm the targeted species. Globally, the production and demand for biopesticides are increasing. In India, biopesticide usage has grown, though it still accounts for only 2.89 % of the total pesticides used. The sector is predicted to grow at a rate of 2.3 % annually. Currently, 12 biopesticides are registered under the Insecticide Act of 1968, including Bt varieties, *Trichoderma*, *Pseudomonas fluoresens* and neem-based pesticides. They lower pest resistance development and have minimal impact on beneficial flora due to their host specificity. Although they are generally more expensive, their reduced application frequency enhances cost-effectiveness. Biodegradability ensures a low residual impact and some formulations exhibit self-perpetuating properties. However, they have a delayed knockdown effect and a shorter shelf life compared to conventional pesticides. Biopesticides are bulkier in carrier form but easier to handle in liquid formulations. They also minimise the risk of pest resurgence and require minimal waiting time before application, making them a preventive and environmentally sustainable pest control option (54).

Bacillus species contribute significantly in disease management and growth enhancement in both potato (*Solanum tuberosum*) and sweet potato (*Ipomoea batatas*). In potato, endophytic *Bacillus* sp. K 9 has been shown to reduce common scab caused by *Streptomyces scabies*, resulting in a yield increase of approximately 12.4 % (55). A combined application of *B. subtilis* and *B. amyloliquefaciens* effectively suppressed *Rhizoctonia solani*, lowering disease incidence from around 41 % to 12 % and increasing tuber yield by 8.2 t/ha. These treatments also improved chlorophyll and carotenoid levels, stem growth and overall plant height (56). A microbial consortium containing *B. subtilis* and *Trichoderma harzianum* reduced scab severity by 30.6-46.1 % and enhanced yield by 23-32 % over two growing seasons (42). *Bacillus* strains offer antiviral and postharvest protection as well. *B. subtilis* (strain 10-4), in combination with salicylic acid, reduced *Phytophthora infestans* induced late blight in storage by 30-40 %, decreased oxidative damage and glycoalkaloid levels and improved tuber nutritional quality (57). Another *B. subtilis* strain lowered *Potato Virus Y* severity by about 66 % by boosting RNase activity and triggering a hypersensitive response (58). Field applications of *B. subtilis* and *B. amyloliquefaciens* promoted earlier emergence, increased plant biomass and height and improved tuber yield by approximately 9 % in off-season cultivation (59). When combined with farmyard manure, *B. subtilis* reduced late blight severity by around 60 % and nearly doubled yield from 11.6 to 25.2 t/ha (60). In sweet potato, *B. velezensis* T 149-19 and *B. safensis* T052-76 effectively controlled foot rot caused by *Plenodomus destruens* in pot experiments. Genome analysis revealed the presence of key biosynthetic genes for antimicrobial compounds such as surfactin, fengycin and bacillibactin (61). Inoculation with these strains increased tuber fresh weight by up to 11.4 % and tuber number by 15-16 %, demonstrating their potential as plant growth promoting rhizobacteria (PGPR) (62).

Aspergillus niger has shown significant biocontrol potential against key fungal pathogens affecting potato (*Solanum tuberosum*), particularly *Fusarium* species and *Phytophthora erythroseptica* (pink rot). Strains of *A. niger* isolated from soil and compost produce a range of bioactive metabolites both volatile and non-volatile as well as organic acids that inhibit pathogen growth. Culture filtrates of *A. niger* reduced *Fusarium sambucinum* lesion size by approximately 76 % and penetration depth by 77 % on infected tubers (63). Similarly, cell-free filtrates applied at 20 % v/w concentration lowered pink rot severity by up to 85 % (64). Beyond these targeted effects, *A. niger* has demonstrated broad-spectrum antagonism, effectively suppressing *Pythium ultimum*, various *Fusarium* species and *Phytophthora erythroseptica*, all of which contribute to postharvest losses (65). In large-scale screening trials, *A. niger* was one of the most effective candidates among 149 fungal isolates, completely inhibiting the germination and growth of *Phytophthora infestans*, the causative agent of late blight. This highlights its potential as a versatile and eco-friendly biocontrol agent for potato health management (66).

Formulation of Plant Growth Promoting Microorganisms (PGPM) inoculants

PGPM inoculants contain one or more strains of microorganisms along with a carrier material (67). They can be applied based on necessity and the crop. PGPMs can be applied either directly to plant material (e.g., seed treatment or root dipping) or to the soil. Soil inoculation often requires larger quantities of inoculant and both solid and liquid formulations can be used for soil inoculation. Liquid formulations can also be applied through fertigation systems, delivering the inoculant as close as possible to the plant's root system (67).

In tuber crops, effective delivery of PGPM inoculants is crucial for successful colonisation and plant benefit. For seed or planting material treatment, common methods include *tuber or cutting coating*, where entities like potatoes, sweet potato vine cuttings or cassava stem cuttings are dipped or coated with microbial suspensions or powdered formulations. This method ensures early root colonisation upon planting and is widely adopted in field and bench-top trials. Soil or rhizosphere applications, such as soil drenching with liquid inoculants at sowing or during early vegetative stages, are particularly effective for crops like cassava and yam, promoting microbial persistence and rhizosphere establishment (68). For potato, seedbed inoculation, where tubers are treated before transplantation, can significantly enhance root-microbe interactions. In furrow or band application, inoculants are precisely delivered near emerging roots via furrow filling or banded placement, increasing microbe plant contacts (68). Foliar sprays are occasionally employed for microbes with systemic or biocontrol functions, offering defence induction against foliar pathogens. For postharvest protection in storage, tuber coating or curing with antagonistic microbes like *Trichoderma* or *Bacillus* strains is used to reduce storage disease incidence (67).

Formulation strategy greatly influences choice of application. Solid carrier formulations (e.g., peat, vermiculite, clay) are suited for seed or tuber coatings and furrow placement, offering longer shelf life but requiring care to preserve viability upon drying (69). Liquid formulations, enriched with dispersing agents like glycerol or CMC, facilitate application via irrigation or foliar spray, but need cold storage to maintain microbial viability. Overall, the selection of inoculation method and formulation depends on the target crop's root morphology, planting system, environmental conditions and microbial compatibility (70).

Efficiency of PGPM inoculant formulations in tuber crops

The success of PGPMs in field applications, especially in tuber crops, relies heavily on the efficiency of their formulations. Efficient formulations ensure prolonged microbial viability, stress tolerance, ease of application and effective colonization of plant roots. Key factors influencing efficacy include the type of carrier material, presence of protective additives and the formulation method.

Carrier-based solid formulations (e.g., peat, talc, vermiculite, compost) are widely used and cost-effective. For example, talc-based *Bacillus* formulations maintained high viability over 6 months and improved yield in potato trials under various agro-climatic conditions. Compost-based carriers offer dual benefits of microbial delivery and nutrient enrichment, further enhancing growth response in sweet potato and cassava (71). Liquid inoculant formulations, especially those supplemented with stabilizers like glycerol, polyvinylpyrrolidone (PVP) and trehalose, have shown superior microbial survival and quicker plant response due to easier root colonization and compatibility with fertigation systems. For instance, liquid formulations of *Bacillus* spp. recorded better root colonization and disease suppression in potato compared to dry powders (72). Encapsulated polymer formulations using sodium alginate, chitosan, or hydrogel matrices are particularly efficient under harsh environmental conditions. These protect microbes from desiccation and UV exposure and ensure gradual release near root zones. In controlled trials, alginate-encapsulated PGPMs significantly increased tuber biomass in sweet potato, with better survival rates than non-encapsulated cells (73). Formulations enhanced with biocompatible additives like carboxymethyl cellulose (CMC), skim milk, or humic acid also improve the shelf life and stress tolerance of microbial cells, boosting colonization efficiency post-application (74).

Ultimately, the efficiency of PGPM formulations lies not just in the choice of microbes, but in how well they are delivered, survive and perform in the field. High-quality formulations can dramatically improve the success of biofertilizer use in tuber crops, leading to enhanced yield, disease resistance and nutrient uptake, making them a viable alternative to chemical inputs in sustainable agriculture.

Mechanism of microbial effect

Direct mechanisms

Direct pathways enhance nutrient acquisition or modulate plant hormones. For example, phosphorus, often immobilised after chemical fertiliser application, becomes available to plants through microbial solubilisation (75). PSB produce enzymes such as phytin that release phosphorus from organic compounds. Iron, similarly, can be made available by microorganisms through the production of siderophores, which form complexes with iron that plants can assimilate (76). *Rhizobium* and *Azotobacter* are N_2-fixing bacteria that convert atmospheric nitrogen into ammonia (77). In addition, microorganisms like *Pseudomonas*, *Agrobacterium*, *Azospirillum* produce plant hormones, such as cytokinins, gibberellins and auxins or reduce ethylene levels, which inhibit plant growth at high concentrations. For instance, microorganisms like *Bacillus* spp., *Pseudomonas fluorescens* and *Trichoderma* spp. produce ACC deaminase, which lowers ethylene production, thus promoting plant growth (77).

Indirect mechanisms

Indirect mechanisms primarily involve competition for resources or the suppression of pathogens. Beneficial microorganisms can outcompete pathogens for nutrients and space, limiting the pathogens' ability to infect plants (78). Siderophore production also indirectly suppresses pathogens by depriving them of iron (79, 80). Microorganisms can also produce antibiotics, such as pyrrolnitrin, iturine and syringomycin, which inhibit pathogen growth (81, 82). Additionally, volatile organic compounds (VOCs) like dimethyl disulfide and dimethyl-hexa-decylamine exhibit both antimicrobial properties and plant growth promotion (83, 84). Furthermore, some microorganisms like *Trichoderma* spp. parasitise pathogens by secreting enzymes that degrade the pathogen's cell walls (85, 86). Induced systemic resistance (ISR) is another indirect mechanism where microorganisms trigger a plant's internal defence systems, enhancing its resistance to phytopathogens (87, 88). The various mechanisms of action in tuber crops and their impact are depicted in Fig. 1 and 2 respectively.

Bioinoculants in tuber crops

Potato

Sphingomonas sp. T168, Streptomyces sp. R170, Streptomyces sp. R181 and Methylibium sp. R182 have been shown to enhance plant growth by producing growth-promoting substances in potatoes. R170 showed the highest potential as a bioinoculant, as indicated by its significant ability to produce plant growth-promoting substances, its higher tolerance against NaCl (2 %) and $AlCl_3$ (0.01 %) and its growth in a wider range of pH values (5.0-10.0) than the other three strains. The compatibility of R170 with other strains showed that the co-inoculation of R170 with T168 or R182 synergistically increased plant weight over un-

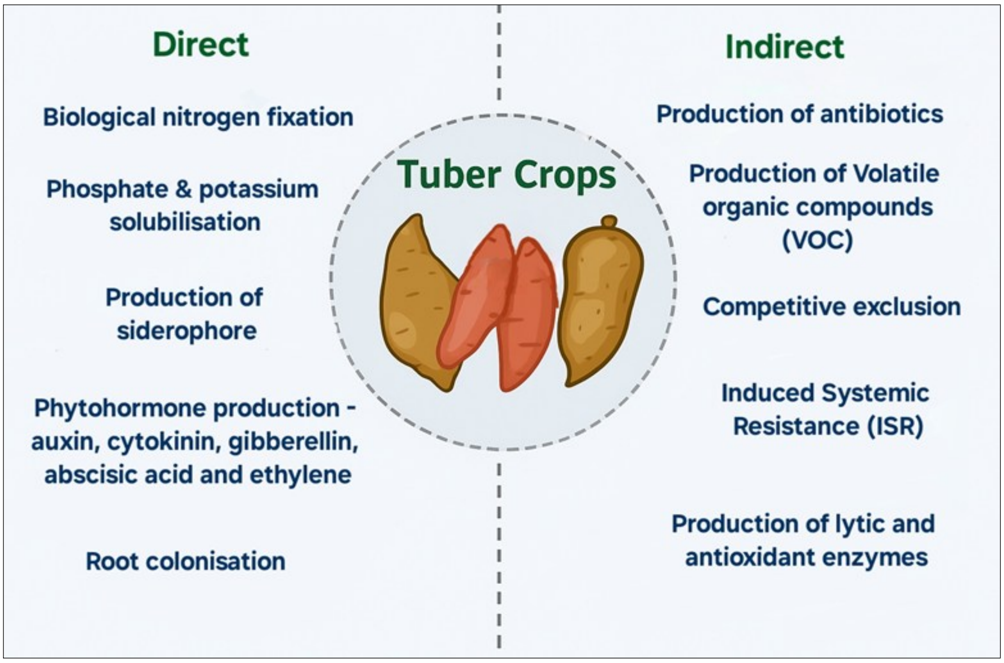

Fig. 1. Direct and indirect action of bioinoculants in tuber crops.

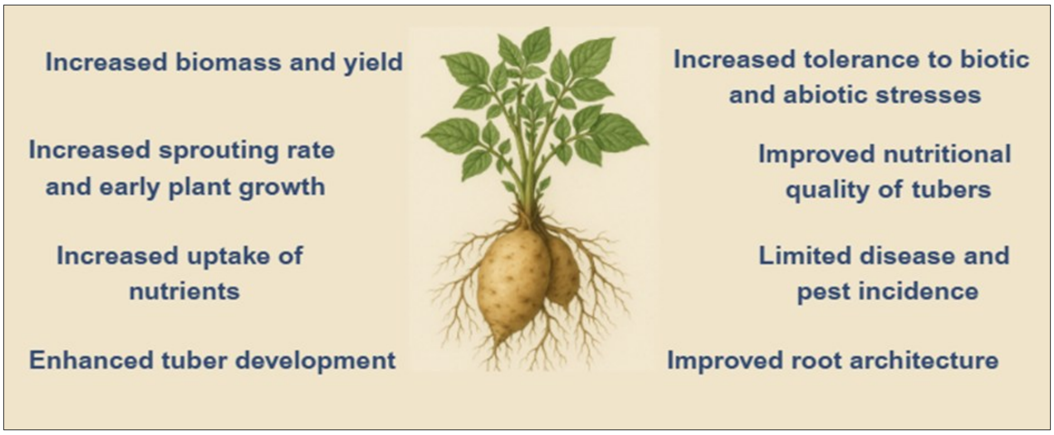

Fig. 2. Impact of bioinoculants on tuber crops.

inoculated controls, indicating the compatibility of strains based on the increased production of plant growth promoters such as Indole-3-acetic acid (IAA) and siderophores, as well as co-localisation on roots. Here, the microbial strains R170, R181, T168 and R182 were cultured and adjusted to a concentration of 1×10^8 CFU/mL. For inoculation, 1 mL of each bacterial suspension was applied directly to individual potato seeds for single-strain treatments. In co-inoculation treatments, 2 mL of mixed suspension-comprising 1 mL from each compatible strain-was applied per seed. The treated seeds were sown in pots containing approximately 100 g of sterilised seedling-raising soil (89).

Bacillus cereus and *Achromobacter xylosoxidans*, isolated from healthy solubilising sweet potato roots, are capable of synthesizing IAA and help to solubilise rock phosphate. Phosphate bacterial isolates were inoculated into National Botanical Research Institute's Phosphate (NBRIP) broth at 3.5×10^7 CFU/mL and incubated at 28 °C for 7 days to assess phosphate solubilization activity. For evaluating plant growth-promotion potential, potato tuber pieces were coated with liquid cultures of the selected isolates using 10 % Arabic gum as an adhesive and planted in sterilized soil-sand-vermiculite mix supplemented with rock phosphate under pot conditions. When used as bioinoculants for potato tubers, they resulted in notable enhancements in vegetative growth, photosynthetic pigments and nutrient concentrations, providing a sustainable alternative to chemical fertilisers (90). The introduction of *Acinetobacter rudis* as a phosphorus-solubilizing bacterium resulted in significant improvements in Lady Rosetta potato germination, tuber weight, size and overall plant height, highlighting its potential as an alternative PSB. While the *Acinetobacter rudis* culture was applied in a carrier mixture of 90 % FYM and 10 % rock phosphate with 30 % moisture, the exact CFU count of the microbial inoculant was not specified in the study (89).

Moreover, bioinoculants can support potato resilience to water scarcity by improving water use efficiency, particularly mycorrhizae, which promote growth and yield under reduced irrigation levels, thereby contributing to sustainable agriculture practices. A combination of reduced irrigation and mycorrhizal inoculation demonstrated optimal yield and quality in potatoes (30). Three types of microbial bioinoculants - Biogen (a bacterial inoculant), Mycorrhizen (a mycorrhizal fungal inoculant) and a mixture of both were used. Where each bioinoculant treatment was applied at a rate of 25 g per planting hole just before sowing the potato seeds. For the Biogen treatment, the contents of the inoculum bag were mixed with gum (supplied with the product) and then placed in the planting hole at 25 g per plant. In the Mycorrhizen treatment, the fungal inoculum-consisting of spores, infected root pieces and soil-was mixed with a sugar solution (prepared by dissolving 100 g of sugar in 100 mL of water). This mixture was also applied at 25 g per planting hole immediately before sowing. In the mixed inoculant treatment, equal amounts of Biogen and Mycorrhizen (i.e., 12.5 g of each, totalling 25 g) were thoroughly combined and then placed in the planting hole just before seed placement. The control treatment received no microbial inoculant. These applications were carried out in containers filled with sandy soil, each container measuring 0.80 m × 0.30 m × 0.40 m and the experiment followed a split plot design with three replicates per treatment. The rhizobacterial strain *Enterobacter cloacae* used at a concentration of 10^8 CFU/mL enhances phosphate solubilization while producing siderophores and amylase. Infected potato plants exhibited improved growth metrics compared to controls, including root and shoot lengths and biomass (91).

To combat *Streptomyces* and *Rhizoctonia* infections, a study assessed the effectiveness of two microbial inoculants on potatoes. The combinations of *Trichoderma atroviride*, *Pseudomonas putida* and *Bacillus subtilis* were noted in one group, while *Pseudomonas protegens* and others were in another. The inoculants were used at 10^8 CFU/mL. Equal volumes of the individual cultures were combined to form the inoculant mixtures. At planting, 100 mL of each inoculant suspension was applied per tuber. Although disease severity fluctuated annually, the combination of biocontrol and biofertilizer properties was particularly effective at minimising tuber damage during periods of high pathogen incidence (92).

Utilising a randomised block design, another study explored the impact of microbial inoculants alongside varying urea and superphosphate levels on soil fertility and potato yield. The combination of AMF, *Bacillus subtilis* and nitrifying bacteria yielded the best results in terms of tuber quantity, weight, moisture and nodes per tuber. The starter inoculum of *G. mosseae*, containing 84-88 % root colonisation and 720-730 spores/g (w/w), was used and mass-multiplied for 90 days using a sterile sand-soil mixture (1:3) with barley as the host. *Bacillus subtilis* (MTCC 1305) was cultured in Luria-Bertani broth and incubated at 37 °C in a BOD incubator. *Nitrosomonas sp.* (NCIM 5071) and *Nitrobacter sp.* (NCIM 5062) were grown in ammonium-calcium carbonate medium and nitrite-calcium carbonate medium, respectively, each incubated at 28 °C for three weeks. These microbial cultures were mass-produced without further purification and used in the field experiment. These results indicate that integrating bioinoculants with reduced fertilizer inputs can enhance yield while preserving soil fertility and lowering chemical fertilizer costs (93).

Cassava

Treating cassava stem cuttings (setts) with a mixture of *Azotobacter* culture and vermicompost (in a 1:1 ratio) prior to planting has shown to be an effective method for inoculation. This technique boosts the plant's nutrient absorption capabilities, fostering more robust root and shoot development (94). The bioinoculants were applied at a uniform rate of 5 kg/ha for each treatment combination, while *Trichoderma* was included in all bioinoculant treatments except the uninoculated control. This significantly decreased the incidence of root rot in cassava, which in turn enhanced yield and nutrient uptake. Additionally, using *Azospirillum*, increased cassava yields even when applying just 50 % of the recommended NPK fertiliser, indicating that bioinoculants can improve nutrient efficiency and lower reliance on chemical fertilizers. Inclusion of AMF and PSB enhanced the absorption of crucial nutrients (nitrogen, phosphorus and potassium) in cassava, contributing to an improved harvest index, even at reduced NPK levels (95).

When the recommended doses of NPK fertilizers are combined with biofertilizers, there is a significant boost in growth metrics and dry matter production, alongside increased tuber yield. The integration of biofertilizers into progressively marginal soils for cassava cultivation replenishes soil nutrients that have been depleted and enhances nitrogen use efficiency. Biofertilizers can positively affect highly weathered and leached soil types such as Oxisols, Ultisols and Alfisols where cassava is grown in tropical regions, thus contributing to environmental conservation. Soils treated with biofertilizers exhibit improved stability and resilience concerning their functional characteristics. Agriculture bio-waste materials composted by anaerobic digester (AD) and inoculated with broad-spectrum inoculants OTAI AG® and Oso Bio-Degrader (OBD-Plus®) microbial inoculants were used. OBD biofertilizer is produced through the composting of agricultural bio-waste materials using anaerobic digestion. During this process, a consortium of broad-spectrum microbial inoculants, specifically OBD-Plus® and OTAI AG®, is added to the composting mixture to enhance the degradation process and enrich the compost with microbial populations beneficial for soil and plant health. The biofertilizer was used both alone and in combination with inorganic fertilisers. The treatments included: OBD applied alone at 2.0, 3.0, 4.0 and 5.0 tonnes per hectare (t/ha); OBD combined with NPK (15:15:15) fertiliser at 300 kg/ha in combinations of 1.0, 2.0, 3.0 and 4.0 t/ha of OBD. The combination of 4.0 t/ha OBD + 300 kg/ha NPK resulted in the highest cassava root yield (31.2 t/ha) (96). The soil microbiome significantly contributes to the secondary genome of host plants, aiding in reducing pathogen virulence and enhancing the development of high-yielding cultivars, which fosters favourable growth conditions. This dynamic shows a profound interdependence between the microbiome and cassava crops. For sustainable agriculture, utilising biofertilizers in rhizosphere management can mitigate reliance on chemical fertilisers while bolstering productivity. Furthermore, employing cassava cultivars for soil phytoremediation and bioenergy crop production in the tropics might revolutionise regenerative agriculture practices for managing xenobiotic pollution, especially when combined with genetic engineering and biofertilizers. The use of biofertilizers in cassava farming underscores their importance for regenerative agriculture, which is essential for food security and aligns with the Sustainable Development Goals (SDG) (97).

Sweet potato

The application of biofertilizers, including AMF and *Pseudomonas fluorescens*, has been demonstrated to significantly boost sweet potato yields. For example, in Uganda smallholder farms, sweet potato yields on an average 4.5 t/ha, while the potential can reach up to 45 t/ha. A study across two agro-ecological zones assessed the effects of biofertilizers, specifically AMF, in conjunction with various phosphorus (P), nitrogen (N) and potassium (K) fertiliser treatments on the NASPOT 11 cultivar. Rhizatech and Symbion VAM Plus were applied at rate of 50 g/m^2 and 1.3 g/m^2, phosphorus fertilizer (triple super phosphate) was applied at graded levels ranging from 0 to 60 kg/ha. Blanket doses of 90 kg/ha nitrogen and 100 kg/ha potassium were also applied, with one-third at planting and the remaining two-thirds top dressed two months after planting. The results were influenced by the soil types and seasons, showing the highest yield of 34.6 t/ha with a mixture of 90 kg N/ha, 100 kg K/ha and 30 kg P/ha. The data indicates that biofertilizers can enhance yields, particularly when paired with N and K, emphasizing the importance of starter nutrients for AMF root colonization in nutrient-poor soils (98).

In former studies, the tuber weight and quantity of sweet potato variety Awachy-1 remained consistent across all treatments, while the variety Racing exhibited an increase. Moreover, reducing fertiliser doses by up to 75 % did not impact the nitrogen and phosphorus levels in the soil when diazotrophic bacteria (including *Azotobacter*, *Azospirillum* and *Acinetobacter*) were used alongside phosphate-solubilising microbes (such as *Pseudomonas* and *Penicillium*). The microbial population density was maintained at a minimum of 10^7 CFU mL^{-1} for bacteria and 10^5 CFU Ml^{-1} for fungi. Both sweet potato varieties produced similar numbers of tubers in each plot despite differing fertiliser applications. The use of biofertilizer allowed for a 75 % decrease in chemical fertiliser use without reducing yield. However, a 50 % reduction in chemical fertilisers led to lower production. The sweetness of the tubers, determined by consistent brix readings, remained unaffected by any of the fertiliser treatments. The findings suggest that biofertilizers could replace up to 25 % of chemical fertilisers while maintaining soil nitrogen and phosphorus availability and achieving similar tuber yields and quality (99).

Yam

For yams, previous researchers highlighted significant alterations in bacterial communities at the genus level following inoculation, especially 16 weeks after planting, where all inoculated genera were more dominant compared to control samples. 100 mL of bacterial inoculum per plant was applied to the top of soil per application. However, no notable differences in growth parameters or nitrogen content were recorded across treatments. At 20 weeks post-planting, the prominence of *Stenotrophomonas* in the inoculated roots diminished, indicating a decrease in inoculation effects. The *Allorhizobium-Neorhizobium-Pararhizobium-Rhizobium* clade was consistently the dominant group (>1 % relative abundance) across all samples, suggesting its critical role in water yam growth (100).

In the case of elephant foot yam, organic farming practices were found to improve canopy growth and corm biomass, as well as reduce the collar rot disease. Organic corms demonstrated 7 % more dry matter, 13 % higher starch content, 12 % more crude protein and 21 % reduced oxalates compared to their conventional counterparts. The mineral content (K, Ca and Mg) also saw an increase of 3-7 %. After five years, plots cultivated organically exhibited a pH improvement of 0.77 units, 19 % increase in organic carbon and enhanced soil properties, which included lower bulk density (2.3 %), increased water holding capacity (28.4 %) and better porosity (16.5 %). The incorporation of bioinoculants like *Trichoderma harzianum, mycorrhiza, Azospirillum and Phosphobacterium* played a crucial role in achieving these results. They were inoculated at a rate of 5 L/ ha. Consequently, yield increased by 20 % (57.1 t/ha), leading to a 28 % higher net profit and an additional income of ₹47716/ha. Lastly, a study revealed that a blend of 50 % recommended nitrogen (RDN) from inorganic fertilisers and 50 % from vermicompost significantly enhanced plant growth, canopy spread and leaflet count at 120 and 150 days after planting (DAP). This combination also yielded the highest harvest index (51.77 %), fresh corm weight (1.267 kg) and overall yield (26.37 t/ha). The use of bio-fertilisers further elevated growth, yield and quality parameters, highlighting the advantages of integrating both organic and inorganic nutrient sources (101). This indicates that organic farming using bioinoculants ensures sustainable yields, high-quality tubers and improved soil health.

Coleus

Glomus fasciculatum and *Trichoderma viride* significantly promote growth yield and disease resistance in *Coleus forskohlii*, although they do not have a direct impact on forskolin content. Research indicates that these bioinoculants enhance plant health and productivity while also mitigating disease occurrence. AMF (*Glomus fasciculatum*) and *Pseudomonas fluorescens* have been shown to increase plant height, spread and branching, resulting in a dry root yield increase of 129-200 % compared to control groups. *Pseudomonas fluorescens* was introduced at a population of approximately 2.2×10^4 CFU per gram of soil in the rhizosphere prior to transplanting and maintained throughout the study and *Glomus fasciculatum* was applied at a density of 1200 infective propagules per gram of carrier inoculum. (102). The combination of *Pseudomonas monteilii* and *Glomus fasciculatum* significantly improves growth parameters such as plant height and tuber yield by boosting nutrient absorption (N, P, K). *Glomus fasciculatum* was used at an inoculum density of 5.3 ± 1.3 infecting propagules per gram of sand soil mix and *Pseudomonas monteilii* at 1.25×10^{11} CFU per batch of inoculation (103, 104). Additionally, bioinoculants are effective in managing root-rot and wilt diseases caused by *Fusarium chlamydosporum* and *Ralstonia solanacearum*. Treatments incorporating *Glomus fasciculatum, Pseudomonas fluorescens and Trichoderma viride* reduce both the incidence and severity of these diseases (103, 105). The combination of *Trichoderma viride and Glomus mosseae* yields the most successful results in controlling disease severity, surpassing the effectiveness of chemical fungicides. The number of infective propagules (ip) in the inoculum for *Glomus mosseae* was 106/g. The Inoculum contained 8×10^5 cfu of *Trichoderma*/ml suspension and 24×10^5/ml inoculum for *P. fluorescens*. (105).

While bioinoculants do not directly influence forskolin content in roots, they significantly enhance overall forskolin yield due to increased root biomass. Treatments using *G. fasciculatum*, neem cake and *P. fluorescens* result in a 159-227 % increase in forskolin yield (103, 104). Moreover, co-inoculation of *P. monteilii* with *G. fasciculatum* also appears to enhance forskolin content in tubers, suggesting a synergistic effect on the plant's medicinal attributes (103).

Limitations of biofertilisers

Bioinoculants, which are beneficial microorganisms used to enhance plant growth and soil health, face several limitations despite their potential benefits over chemical fertilisers, which can affect their effectiveness and widespread adoption in agriculture. Bioinoculants often show promising results in controlled environments like greenhouses, but their effectiveness can be inconsistent in open fields. This variability is attributed to environmental factors such as soil type, moisture levels, temperature and native microbial communities, which can limit the inoculant's success. For example, a bioinoculant that works well in one type of soil may not perform equally well in another due to differences in soil pH or nutrient availability (106). Another challenge is that the inoculated microbes have a limited life span in the soil. The introduced microbes often struggle to compete with native soil microorganisms and may fail to establish themselves or remain viable long enough to benefit the plants. Environmental stresses like drought or extreme temperatures can further reduce the survival rates of bioinoculants (88).

Bioinoculants often have a limited shelf life because they contain live microorganisms. They require specific storage conditions, such as low temperatures, to remain viable and any deviation from these conditions can reduce their efficacy. Poor storage practices can lead to the death of the inoculants or a significant decrease in their effectiveness (107, 108). Some bioinoculants are highly specific in terms of their interaction with host plants, limiting their application. For instance, certain strains of rhizobia form symbiotic relationships only with specific legume species, meaning they cannot be applied broadly across different crop types. This host specificity can limit the wide-scale adoption of some bioinoculants. The production and commercialization of bioinoculants are often more expensive compared to chemical fertilisers and pesticides, especially in large-scale operations. High production costs, coupled with the need for specialised knowledge for application, can make bioinoculants less attractive to farmers, particularly in developing countries, resulting in low adoption rates (108).

There is a potential risk that bioinoculants could inadvertently introduce pathogenic strains into the environment, especially when quality control is inadequate during production. This could lead to the spread of harmful organisms that negatively impact crops or soil health (87). The lack of uniform global standards and regulations concerning the production, quality and application of bioinoculants is a significant challenge. Different countries have different regulations, which can create barriers to international trade and hinder the development of a robust global market for bioinoculants (67, 88). The measurement of the persistence of the colonisation by PGPM and their persistence in the soil proves to be difficult because they have to be identified from a mixed culture (109).

To overcome these limitations, several mitigation strategies have been developed to enhance the effectiveness and reliability of bioinoculants. Improved formulation technologies such as the use of advanced durable carriers like peat, talc, vermiculite and biodegradable polymers (e.g., alginate beads) help to protect microbial viability and function under various environmental conditions (110). Liquid formulations fortified with stabilisers such as glycerol, polyethylene glycol (PEG), polyvinylpyrrolidone (PVP), carboxymethyl cellulose (CMC), trehalose and skim milk have demonstrated extended shelf life of up to 19-25 months and greater tolerance to environmental stress (70). Additionally, selecting stress-tolerant or engineered microbial strains-such as psychrotolerant PGPMs for cold regions or drought-resistant strains for arid environments can significantly improve field performance (111). Standardizing production through precision formulation and quality control, including viability assays and clear labelling (propagule count, expiration, storage instructions), ensures consistency and efficacy, especially for AMF inoculants (112). Furthermore, the integration of nanotechnology has led to the development of nano-biofertilizers, which allow for controlled nutrient release, enhanced microbial survival and prolonged shelf life. Encapsulation supports gradual microbial release, maintaining viability and activity against soil pathogens for prolonged periods. Shelf life of 5-6 months or longer is achievable under ambient conditions using encapsulated cells enriched with humic acids (72). Collectively, these strategies aim to address the practical challenges of bioinoculant use, making them more viable for sustainable agriculture, including in tuber crop systems (Fig. 3).

Future prospects

The future of bio-inoculants is promising, with the potential to revolutionise agriculture by providing sustainable alternatives to chemical inputs. As the population increases worldwide and environmental problems escalate, the need for clean and residue free agriculture is increasing (113). Bio-inoculants offer solutions to issues such as degradation of soil health and greenhouse effect and advancements in biotechnology are improving their effectiveness (114, 115). Enhancing the quality of bioinoculants involves several strategies, including optimizing microbial inoculum preparation, encapsulating microbes for better survival in the soil and developing fermentation techniques that improve the utilisation of nutrients and yields (116). Protocols ensuring quality, like microbial viability tests and contamination prevention, ensure that bio-inoculants meet regulatory standards and deliver consistent results (117).

Encouragingly, the adoption of organic farming is driving demand for bio-inoculants, as society today is conscious about health and the environment. Policies that promote organic cultivation, provide incentives for manufacturing bioinoculants and include regulatory measures like organic certification are increasing the value of the market by creating new opportunities in production, research and distribution (118).

Technological innovations in formulation & delivery

Emerging delivery systems such as nano-biofertilizers, encapsulated carriers and sustained-release formulations are poised to enhance inoculant efficiency. Nano-biofertilizers, which combine microorganisms with nanoparticles (e.g., chitosan, zeolite), improve stress tolerance, nutrient availability and microbial survival under field conditions. Encapsulation in polymers or hydrogels offers controlled release and protection from environmental stresses, boosting root colonisation and consistency in tuber crops (119).

Expanding microbial consortia

Instead of single strains, research is shifting toward synergistic consortia, e.g., combining PGPR, AMF and biocontrol agents, to expand functional traits like nutrient uptake, stress tolerance and disease resistance. Such consortium-based strategies promise more resilient performance across varied agricultural conditions (71).

Precision agriculture & tailored inoculants

Optimising inoculant performance includes region- or genotype-specific formulations aligned with local soil characteristics, climate and crop varieties. Leveraging microbiome profiling and omics technologies helps customise bioinoculants to specific agroecosystems, enhancing root establishment and functionality (120).

Regulatory frameworks & quality assurance

A unified regulatory landscape is emerging, especially in the EU, to standardise bioinoculant production, labelling and quality control. Ensuring viability testing, strain verification and sterility

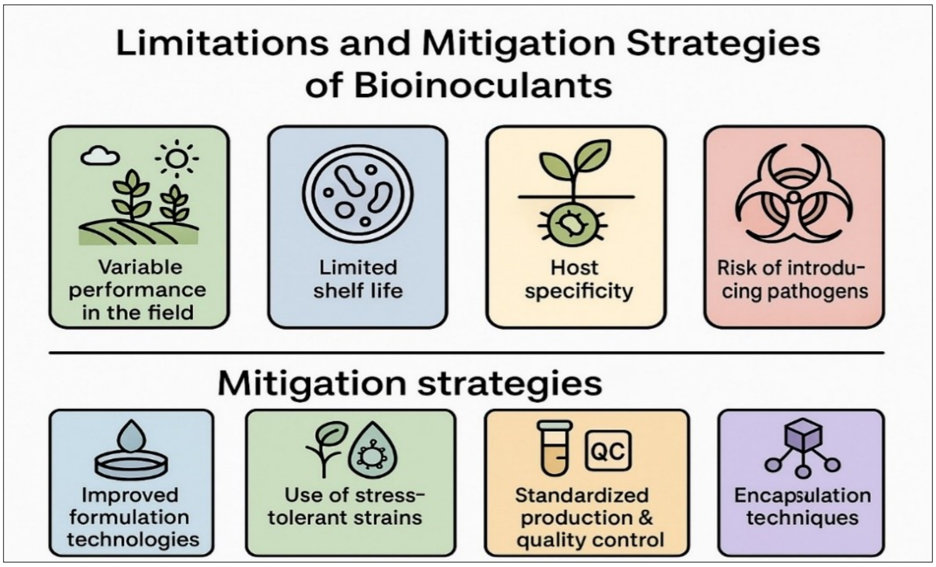

Fig. 3. Limitations of bioinoculants on tuber crops.

is critical for increasing farmer confidence, product efficacy and facilitating international trade (121).

Market trends & policy support

The rapid growth in demand for sustainable and organic agriculture is boosting bioinoculant adoption. Global markets for plant biofertilizers are expected to grow annually by 12 %, reaching millions of USD in the coming years. Supportive policies, subsidies and organic farming certifications further stimulate production, research and distribution, offsetting costs relative to conventional agrochemicals (122).

Integrating with digital & smart farming tools

Precision application of bioinoculants via IoT-driven fertigation, real-time soil monitoring and AI-guided dosing can optimise microbial survival and plant colonisation. These technologies help to reduce product waste and enhance field efficacy, a frontier being actively explored (123).

Conclusion

The integration of bioinoculants into tuber crop production systems has demonstrated significant promise in enhancing plant growth, nutrient uptake, stress tolerance, disease resistance and overall yield. A wide range of microbial strains, including *Streptomyces sp.* R170, *Trichoderma viride*, *Pseudomonas fluorescens*, *Azospirillum spp.*, *Glomus fasciculatum* and *Acinetobacter rudis* have shown effectiveness across diverse tuber crops such as potato, cassava, sweet potato, yam, elephant foot yam and coleus.

Bioinoculant application strategies have varied in terms of formulation and dose, typically ranging from 1×10^7 to 1×10^8 CFU/mL for bacterial inoculants and 1000-7000 infective propagules per gram for mycorrhizal fungi. Carrier-based formulations such as farmyard manure (FYM), Arabic gum, sugar solutions, or composted agrowaste have been successfully employed to improve delivery and colonisation efficiency. Specific examples include - *Streptomyces sp.* R170 (1 mL per potato seed at 1×10^8 CFU/mL) improved biomass and salinity tolerance. *Acinetobacter rudis* in a FYM-rock phosphate carrier enhanced tuber weight and germination. *Trichoderma viride* and *Glomus mosseae*, applied at 106 infective propagules/g and 8×10^5 CFU/mL, respectively, showed superior control of root-rot and wilt diseases in coleus. In cassava, 4 t/ha of OBD-Plus® with 300 kg/ha NPK produced the highest root yield (31.2 t/ha). In elephant foot yam, a combination of *Trichoderma*, *Azospirillum*, *Phosphobacterium* and mycorrhizae applied at 5 L/ha enhanced yield by 20 % over conventional methods. For sweet potato, diazotrophic bacteria and phosphate solubilisers allowed 75 % reduction in chemical fertilisers without compromising yield or quality. Beyond growth promotion, bioinoculants confer multiple ecological and agronomic benefits such as improved water use efficiency, soil fertility enhancement and pathogen suppression, positioning them as a viable, sustainable alternative to synthetic agrochemicals. The synergistic effects of co-inoculations (e.g., *Pseudomonas monteilii* + *Glomus fasciculatum*) further underscore the potential of microbial consortia in increasing both yield and secondary metabolite accumulation, such as forskolin in *Coleus forskohlii*.

In conclusion, precise selection of microbial strains, optimization of doses and matching inoculants with crop and soil conditions are crucial to unlocking the full potential of bioinoculants in tuber crop cultivation. Their adoption not only enhances productivity but also contributes to sustainable agriculture, aligning with long-term soil health and environmental conservation goals.

Authors' contributions

VKV collected the literature and designed the framework of the article, STK drafted the manuscript. TC and AR conceived the study, MP and BD reviewed and added suggestion for improvement, SN and KC participated in the study's design and corrected the article and RR participated in its design and coordination. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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