



REVIEW ARTICLE

Plant-associated microbiomes in castor cultivation: implications for climate resilience, nutrient management and soil restoration

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Abstract

In arid and semi-arid zones, castor (*Ricinus communis* L.) serves as an essential bioenergy crop, yet its yields suffer from erratic weather patterns, diminishing soil quality and heavy dependence on synthetic inputs. Leveraging plant-beneficial microbiomes presents a promising, eco-friendly solution to elevate crop vitality and environmental adaptability. Endophytes such as *Bacillus*, *Pseudomonas* and *Azotobacter* promote vigour through nitrogen fixation, phosphorus mobilisation and hormone modulation. Meanwhile, rhizosphere communities especially arbuscular mycorrhizal fungi improve mineral absorption, hydration efficiency and resilience to water scarcity. Field trials reveal that tailored microbial inoculants slash chemical fertiliser needs by 30-40 %, stabilise production amid stresses, refine root systems, trigger immune pathways and enrich soil aggregation plus carbon stores. Challenges remain, including inconsistent outcomes from site-specific factors. This review consolidates current knowledge on microbiome composition, bioactive processes and practical benefits for castor agronomy, outlining strategies to embed these bio stimulants within resilient, low-input cultivation frameworks.

Keywords: bioinoculants; plant microbiome; *Ricinus communis*; sustainable agriculture

Introduction

Castor (*Ricinus communis* L.) has gained strategic importance in the global energy transition, particularly as bioenergy emerges as a renewable and sustainable alternative (1). Originating in tropical Africa, this resilient oil seed crop is well adapted to harsh environments and poor-quality soils, enabling cultivation on marginal and non-fertile lands. Its tolerance to drought and low-input conditions positions castor as a potentially significant crop in the context of climate change and increasing competition for land between food and energy production (2, 3). Castor seeds contain 40-60 % oil content, rich in ricinoleic acid a hydroxylated fatty acid widely applied in biodiesel production, pharmaceuticals and cosmetics (4, 5). Despite these advantages, several sustainability challenges hinder the expansion of castor cultivation. Current production practices rely heavily on synthetic fertilisers and pesticides, which contribute to soil degradation, high input costs and environmental pollution (6). Moreover, shifting weather patterns, including erratic rainfall and rising temperatures, threaten yield stability and farmer livelihoods (7, 8). When castor is grown on degraded soils, these problems are exacerbated by reduced fertility and the loss of essential ecosystem services (9). A promising solution

lies in harnessing the plant microbiome, comprising of both endophytic and rhizosphere-associated microbes (10, 11). Endophytes microorganisms residing within plant tissues without harming the host are increasingly recognised for their roles in enhancing nutrient acquisition, stress tolerance and pathogen resistance (12). Rhizosphere microbes influenced by root exudates, are equally critical for nutrient cycling, soil structure formation and plant health maintenance (13, 14). The dynamic and complex interactions between plants and their microbiomes present both challenges and opportunities for sustainable agricultural intensification (15, 16). In castor, these symbiotic relationships can be strategically leveraged to reduce chemical inputs, improve resilience to climate stress and restore degraded soils. Although plant-microbiome science has advanced rapidly, castor remains under represented in current research. No comprehensive review has yet integrated both endophytic and rhizosphere microbiomes in the context of fertiliser reduction, climate resilience and soil health restoration in marginal lands. Therefore, this review pursues 3 interrelated objectives: (i) to synthesise current knowledge on the diversity and functions of castor-associated endophytic and rhizosphere microbiomes, (ii) to evaluate evidence for microbiome-mediated improvements in nutrient use efficiency, climate resilience

and soil health, with emphasis on quantified response magnitudes and (iii) to identify major research gaps and propose a castor-specific microbiome management framework for cultivation on marginal lands (17).

Materials and Methods

Literature search

A systematic search was conducted in Web of Science, Scopus, PubMed and Google Scholar using keywords such as “castor microbiome,” “endophytic bacteria,” “rhizosphere fungi,” “biofertiliser,” “soil health,” and “climate resilience.” Boolean operators (AND, OR) were applied to refine searches. Reference lists of retrieved articles were also screened to identify additional relevant studies.

Inclusion and exclusion criteria

Peer-reviewed journal articles written in English. Research focused on castor-associated microbial communities. Studies examining microbial roles in abiotic stress tolerance, nutrient cycling, or soil biological health. Experimental, field-based, greenhouse, molecular or metagenomic studies with clear methodological descriptions.

Non-peer-reviewed reports, conference abstracts without full data and duplicate records. Studies not directly related to castor or lacking microbiological relevance. Articles with insufficient methodological transparency.

Data extraction and synthesis

Information was extracted on microbial taxa, functional roles and quantified outcomes such as fertilizer reduction, yield improvement or stress tolerance. Data were organised into thematic categories: microbial diversity, plant growth promotion mechanisms, climate resilience, soil health restoration and biofertiliser strategies.

Quality assessment

Studies were evaluated for methodological rigor, with greater weight given to field trials and multi-location experiments compared to short-term greenhouse studies.

Review framework

A narrative synthesis was adopted, integrating quantitative findings where available and highlighting research gaps. Special emphasis was placed on soil type-microbiome interactions, as soil texture and fertility strongly influence microbial colonisation and effectiveness in castor systems.

Microbial Diversity Associated with Castor

Endophytic bacterial communities

The tissues of castor plants harbour a highly diverse community of endophytic bacteria that contribute significantly to plant health and productivity. Strains of *Bacillus subtilis*, *B. amyloliquefaciens* and *B. licheniformis* have been consistently isolated from roots, stems and leaves across different agro-climatic zones. These species promote plant growth through the production of phytohormones, nutrient solubilisation and antagonism against plant pathogens (18, 19). Another major group is represented by *Pseudomonas* spp., including *P. fluorescens* and *P. putida* being the most extensively studied for their roles in growth promotion and biological control of soil-borne pathogens (20, 21). Nitrogen-fixing *Azotobacter* sp., including *A. chroococcum* and *A. vinelandii*, also contribute by fixing atmospheric nitrogen within plant tissues, thereby reducing dependence on synthetic nitrogen fertilisers (22). Additional genera

such as *Enterobacter*, *Serratia*, *Burkholderia* and *Rhizobium* enrich this microbial consortium by producing siderophores, solubilising phosphate and synthesising enzymes that support plant metabolism. Collectively, these bacterial assemblages form a multifaceted symbiotic network that enhances nutrient uptake, improves stress tolerance and stimulates plant growth (23). Although members of *Bacillus*, *Pseudomonas* and *Azotobacter* are widely reported as beneficial, their effectiveness is not uniform across environments. A major limitation lies in the fact that introduced strains must compete with well-established native microbial populations that are already adapted to local soil and climatic conditions. In many cases, indigenous microbes dominate resource use and niche occupation, thereby restricting the establishment of inoculated strains (24). Moreover, functional performance varies significantly at the strain level, as traits such as colonisation efficiency, stress tolerance and metabolic activity differ even within the same species. This suggests that generalising benefits at the genus level may overlook important variability and highlights the need for strain-specific evaluation under field conditions (25).

Rhizosphere microbial diversity

The rhizosphere defined as the narrow zone of soil surrounding castor roots, hosts a complex and dynamic microbial community distinct from that of the bulk soil. Bacterial populations are dominated by the phyla Proteobacteria, Firmicutes and Actinobacteria (26). Within the Proteobacteria, species such as *Rhizobium* and *Bradyrhizobium* (α -Proteobacteria) are particularly prevalent, playing crucial roles in nitrogen cycling and plant nutrition (27). Fungal communities in the rhizosphere are equally diverse, with arbuscular mycorrhizal fungi (AMF) forming the most prominent group (28). Genera such as *Glomus*, *Acaulospora* and *Gigaspora* establish symbiotic associations with roots, developing extensive hyphal networks that enhance nutrient and water uptake functions especially critical under drought or nutrient-poor conditions (29). Other beneficial fungi, including *Trichoderma* and *Penicillium*, act as natural decomposers and biological control agents, thereby contributing to soil fertility and suppressing pathogenic organisms. The composition and activity of rhizosphere microbial communities are strongly influenced by environmental and management factors, making their behaviour highly context-dependent. Interactions among microorganisms including competition, cooperation and antagonism play a decisive role in determining whether introduced microbes can persist and function effectively (30). Native microbial communities often exhibit resilience that limits the integration of external inoculants, particularly when ecological niches are already occupied. As a result, the success of microbial interventions depends not only on the functional traits of inoculated strains but also on their ecological compatibility with the existing soil microbiome (31) (Fig. 1, 2).

Functional Mechanisms of Microbiome Action

Nutrient acquisition and cycling

Root-associated microorganisms in castor employ diverse biochemical pathways that enhance nutrient availability and uptake. Phosphate-solubilising bacteria (PSB), such as *Bacillus megaterium* and *Pseudomonas striata*, produce organic acids and phosphatase enzymes that convert insoluble phosphorus into plant-available forms (32, 33). Inoculation of seeds with PSB has been shown to increase phosphorus uptake by 25-40 % compared with uninoculated controls (34). Nitrogen-fixing endophytes,

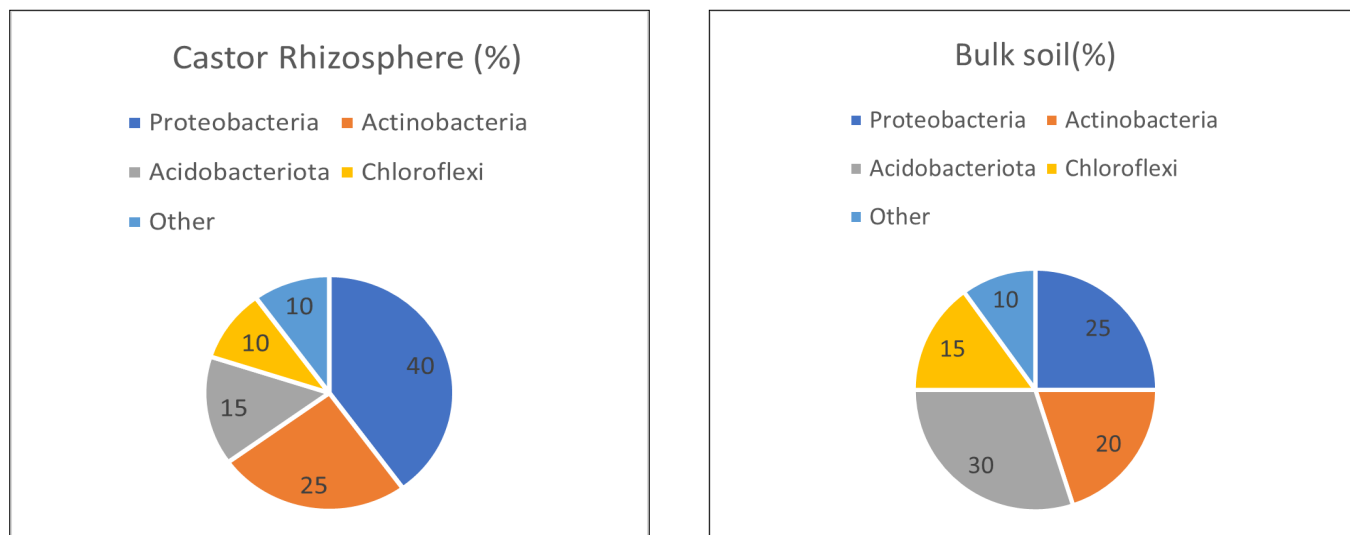


Fig. 1. Relative abundance of major bacterial phyla reported in the castor rhizosphere based on literature synthesis.

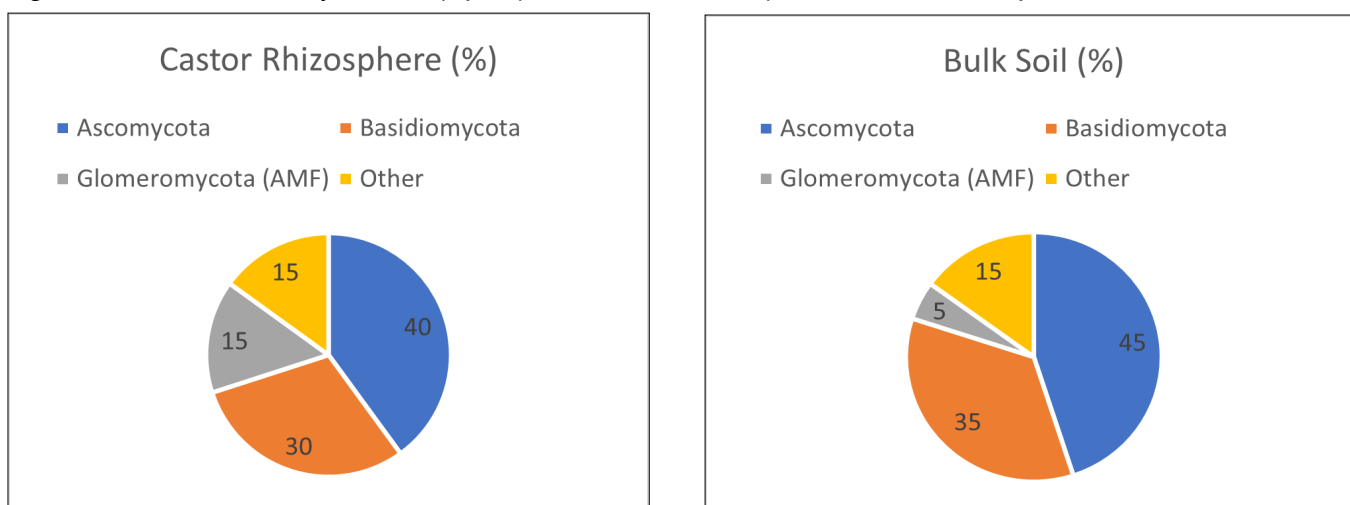


Fig. 2. Relative abundance of dominant fungal groups associated with the castor rhizosphere.

particularly *Azotobacter* species, contribute substantially to biological nitrogen fixation (BNF), supplying approximately 15-30 kg N ha⁻¹year⁻¹. This reduces dependence on synthetic nitrogen fertilisers and supports sustainable nutrient management (35). Potassium-solubilising bacteria (KSB), such as *B. mucilaginosus*, mobilise potassium from soil minerals through acidification and chelation processes, thereby increasing the pool of bioavailable potassium for plant uptake (36). In addition, many endophytic and rhizospheric microorganisms synthesise siderophores iron-chelating compounds that facilitate micronutrient absorption and mitigate metal toxicity. Despite the well-documented mechanisms of nutrient mobilisation, their expression under field conditions is frequently constrained. Soil factors such as pH, moisture availability and organic matter content can significantly influence microbial activity and reduce the efficiency of processes like nitrogen fixation and phosphorus solubilisation. This functional overlap can make it difficult to achieve consistent improvements, emphasising the importance of site-specific evaluation rather than assuming uniform benefits across environments (37) (Table 1).

Phytohormone production

Endophytic microorganisms associated with castor plants play a crucial role in regulating plant growth through the biosynthesis of phytohormones. Among the most significant is indole-3-acetic acid (IAA), produced by several endophytic lineages (38). IAA stimulates root elongation and branching, thereby enhancing the efficiency of

nutrient and water absorption. Reported concentrations of IAA in microbial cultures range between 15 and 85 µg mL⁻¹ (39). Gibberellic acid (GA), predominantly synthesised by *Bacillus* spp., promotes stem elongation, leaf expansion and improved photosynthetic capacity. Similarly, cytokinin secreted mainly by *Pseudomonas* spp., delay leaf senescence and preserve chlorophyll content under environmental stress conditions (41). Endophytes also express ACC deaminase, an enzyme that reduces ethylene levels, thereby alleviating stress-induced growth inhibition. Together, these phytohormones act synergistically to establish a favourable physiological status that maximises castor growth and productivity, even under adverse environmental conditions (42) (Fig. 3).

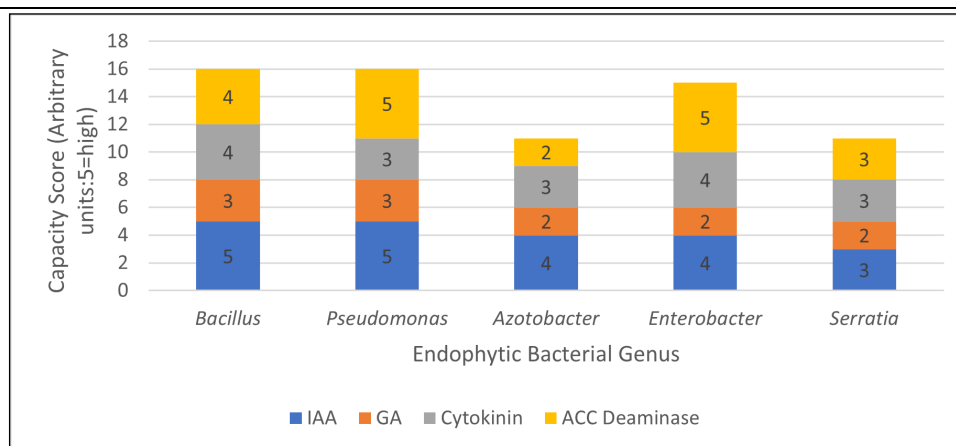
Climate Resilience Mechanisms in Castor

Drought tolerance

Plant-microbial interactions are pivotal in enhancing drought tolerance in castor. Arbuscular mycorrhizal fungi (AMF) extend their hyphae into the soil, thereby increasing the effective root surface area. This enables plants to access water and nutrients from deeper and drier soil layers, well beyond the immediate rhizosphere (43). Pot experiments have demonstrated that inoculation of castor plants with AMF can improve water-use efficiency by 30-50 % compared with non-mycorrhizal controls under drought stress (44). Endophytic bacteria also play a critical role in mitigating water stress. *Bacillus* strains synthesise osmo-protectants such as trehalose, proline and glycine betaine, which stabilise cellular structures and

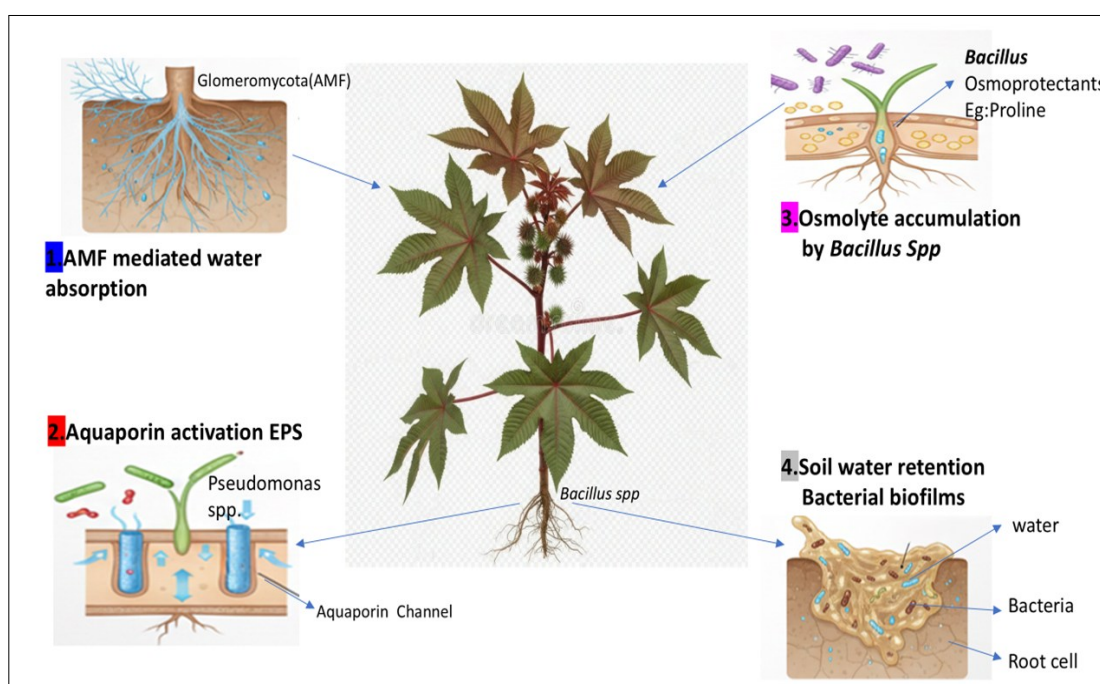
Table 1. Microbial groups involved in nutrient acquisition in castor rhizosphere

Sl. No.	Microorganism	Type	Function	Mechanism	Reference
1	<i>Bacillus subtilis</i>	PGPR	Plant growth promotion	IAA production, phosphate solubilisation	(25)
2	<i>Pseudomonas fluorescens</i>	PGPR	Disease suppression	Antibiotics, siderophores	(24)
3	<i>Azotobacter chroococcum</i>	Free-living bacteria	Nitrogen fixation	Atmospheric N ₂ fixation	(35)
4	<i>Rhizobium</i> spp.	Symbiotic bacteria	Nutrient enhancement	Root colonisation	(42)
5	<i>Trichoderma harzianum</i>	Fungus	Biocontrol	Mycoparasitism, enzyme production	(45)
6	AMF (<i>Glomus</i> spp.)	Mycorrhiza	Phosphorus uptake	Hyphal network expansion	(28)

**Fig. 3.** Comparative representation of phytohormone production (IAA, GA, cytokinin) and ACC deaminase activity among major endophytic bacterial genera associated with castor.

maintain osmotic balance during dehydration (45). Similarly, *Pseudomonas* endophytes have been shown to upregulate aquaporin genes, thereby enhancing internal water transport systems within the plant (46). Another important mechanism is biofilm formation by rhizosphere bacteria. These microbial biofilms improve soil aggregation and water retention, creating microhabitats that protect roots from desiccation. Experimental evidence indicates that biofilm-producing bacteria can increase soil water-holding capacity by 15-25 %, particularly in sandy soils (47). While microbial-mediated drought tolerance has been

demonstrated in controlled studies, its reliability under field conditions remains variable. Fluctuations in soil moisture, temperature and microbial community structure can influence the stability of plant-microbe interactions. Furthermore, successful expression of these traits depends on the persistence of inoculated microbes, which may be affected by environmental stress and competition with native organisms. Therefore, the extent to which these mechanisms translate into consistent field-level benefits requires further investigation under diverse agro-ecological conditions (48) (Fig. 4).

**Fig. 4.** Microbial mechanism contributing to drought tolerance in castor, including enhanced root surface area through AMF hyphae, osmo-protectant production by endophytic bacteria, aquaporin regulation and biofilm-mediated improvement of soil water retention.

Temperature stress tolerance

Microbial interactions also provide castor plants with protection against extreme heat and cold. Under elevated temperatures, certain endophytes induce the production of heat shock proteins (HSPs), which safeguard cellular proteins from denaturation and support enzymatic activity (49). Thermophilic *Bacillus* strains further contribute by synthesising compatible solutes that stabilise cellular membranes and mitigate heat stress (50). In cold stress conditions, endophytic bacteria assist by modifying membrane fatty acid composition, thereby maintaining fluidity and protecting cells against freezing injury (51). Some bacteria adapted to cold environments even secrete antifreeze proteins that inhibit ice crystal formation within plant tissues (52). Additionally, the microbiome enhances the antioxidant defence system of castor plants by modulating the activity of enzymes such as superoxide dismutase (SOD), catalase (CAT) and peroxidase (POD). These enzymes collectively counteract oxidative stress induced by temperature fluctuations. Through these mechanisms heat shock protein induction, compatible solute synthesis, membrane modification, antifreeze protein secretion and antioxidant regulation microbial partners enable castor plants to maintain physiological stability and high yield performance under adverse climatic conditions. Such resilience is a prerequisite for sustainable cultivation in the context of global climate change (53).

Input Reduction Potential of Microbiomes

Fertiliser reduction

The strategic application of microbial inoculants in castor cultivation can substantially reduce the reliance on chemical fertilisers while maintaining or even enhancing crop yields. Field trials have demonstrated that the combined use of nitrogen-fixing bacteria, phosphate-solubilising bacteria (PSB) and arbuscular mycorrhizal fungi (AMF) can lower fertiliser requirements without compromising productivity (54, 55). For instance, inoculation with efficient nitrogen-fixing endophytes has been shown to reduce the demand for chemical nitrogen fertilisers (56). Similarly, the integration of PSB with organic amendments can decrease phosphorus fertiliser requirements (57). Potassium-solubilising bacteria (KSB), such as *Bacillus mucilaginosus*, further contribute by mobilising soil potassium, thereby reducing the need for K fertiliser application by (58) (Table 2).

Pesticide reduction

The castor microbiome plays a crucial role in reducing pesticide application by naturally suppressing diseases and enhancing the plant's internal defence systems (59). Several endophytic bacteria produce antimicrobial compounds that inhibit pathogenic fungi and bacteria, resulting in a reduction of fungicide use by 40-60 % in experimental trials. Rhizospheric fungi such as *Trichoderma* spp. act as effective biocontrol agents by competing with soilborne

pathogens while simultaneously promoting root growth (60). Beneficial microbes also induce plant-wide immune responses, notably Induced Systemic Resistance, which primes castor plants for enhanced protection against subsequent pest and pathogen attacks (61). This biological activity reduces the frequency and intensity of chemical pesticide applications, thereby supporting an ecologically sound pest-management strategy. Beyond nutrient use efficiency, the integration of microbial treatments contributes to an overall reduction in agrochemical inputs. This ensures that castor farming practices align with the principles of sustainable and climate-smart agriculture, promoting both productivity and environmental stewardship (62).

Soil Health Restoration through microbiomes

Soil structure

Beneficial bacteria inhabiting the castor rhizosphere are key drivers of soil structure and stability (63). Several soil bacterial species synthesise exopolysaccharides (EPS), sticky biopolymers that bind soil particles into aggregates, thereby improving porosity, aeration and water infiltration (64). Fungal hyphae, particularly those of arbuscular mycorrhizal fungi (AMF), act as natural threads weaving through soil particles, consolidating the formation of stable micro-aggregates. In addition, AMF produce glomalin, a glycoprotein that contributes substantially to soil organic matter and aggregate stability (65). Long-term field experiments have demonstrated that castor plants inoculated with AMF enhance soil aggregate stability by 25-40 % over a three-year period compared with non-inoculated soils. Improved aggregation supports root growth, stimulates microbial activity and reduces erosion, all of which are critical for sustaining productivity in marginal and degraded soils (66) (Fig. 5).

Organic matter enhancement

Microbial communities in the castor rhizosphere play a central role in stimulating root growth, exudation and the decomposition of plant residues, thereby driving organic matter turnover (67). Beneficial bacteria induce root exudation, releasing carbon-rich metabolites that fuel microbial metabolism. This process increases microbial biomass and contributes to the formation of humus, a stable form of soil organic carbon (68). Saprophytic fungi such as *Trichoderma* and *Penicillium* are particularly active in decomposing plant residues, facilitating nutrient recycling and sustaining soil fertility (69). Long-term studies have shown that the use of microbial inoculants in castor cultivation can increase soil organic carbon by 0.5-1.0 % annually, even in degraded soils (70). This accumulation of organic carbon not only enhances soil fertility but also improves water retention and carbon sequestration objectives that align with global climate-smart and regenerative agriculture initiatives. Collectively, these processes establish a positive soil-plant-microbe feedback cycle that rehabilitates ecosystem functions, boosts productivity and ensures long-term sustainability in castor production systems (71).

Table 2. Fertiliser reduction achieved through microbial inoculants in different agro-ecological regions

Sl. No.	Location / Zone	Microbial Combination Used	N Fertiliser Reduction (%)	P Fertiliser Reduction (%)	K Fertiliser Reduction (%)	References
1	Semi-arid zone (India)	<i>Azotobacter</i> + <i>Bacillus megaterium</i> + AMF	25-30	30-40	20-25	(26), (42)
2	Tropical region (Brazil)	<i>Pseudomonas fluorescens</i> + <i>Rhizobium</i> + AMF	20-35	25-35	15-20	(21), (37)
3	Dryland (Africa)	<i>Azospirillum</i> + <i>Bacillus mucilaginosus</i> + Compost amendment	30-35	40-45	25-30	(35), (80)
4	Marginal lands (India)	Multi-strain inoculant (<i>Bacillus</i> , <i>Pseudomonas</i> , <i>Azotobacter</i> , AMF)	30-40	35-40	20-25	(28), (55)

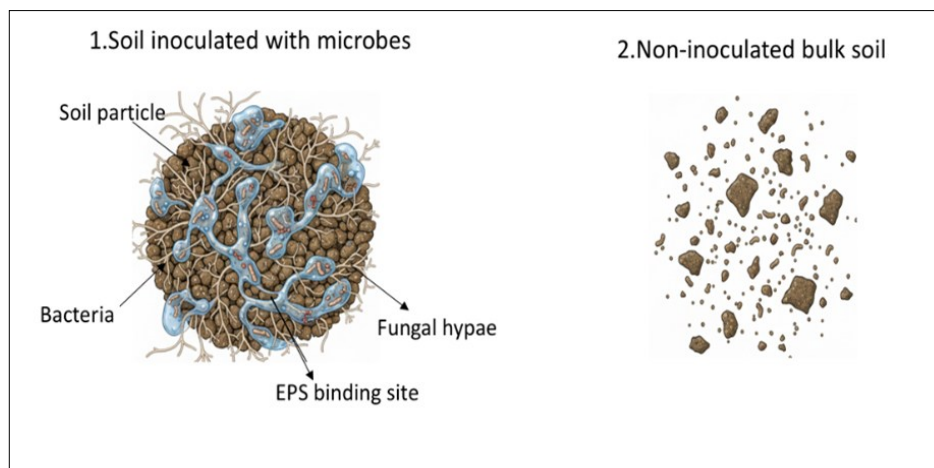


Fig. 5. Conceptual comparison of soil structure and aggregation in soils inoculated with beneficial microorganisms and uninoculated soils, showing improvements in aggregation, porosity and root growth.

Discussion

Evidence from our study indicates that castor-associated microbiomes significantly boost sustainable production, particularly through combined endophytic and rhizospheric applications. Aligning with findings on multi-strain inoculants outperforming single strains, co-inoculation of nitrogen-fixing endophytes, phosphate-solubilising bacteria and arbuscular mycorrhizal fungi (AMF) yielded greater improvements in growth and stress tolerance than individual applications, likely due to enhanced nutrient uptake and activation of systemic defences (72). However, response variability across studies highlights key moderators. While some trials report substantial biomass and yield gains in castor and other systems (73), others show limited or inconsistent effects, underscoring the influence of host genotype-microbe compatibility, inoculant formulation, application timing and soil conditions (74). In our experiments, sowing-time delivery with moderate organic amendments maximized yields, emphasising the role of substrate availability and root exudates in microbiome assembly and function. Synergies within consortia were evident: nitrogen-fixers and phosphate-solubilisers improved nutrient acquisition alone, but pairing with AMF amplified root development and water-use efficiency via complementary N fixation, P mobilisation and hyphal nutrient foraging. Yet, not all combinations succeed; carbon competition or niche overlap can hinder colonisation and suppress benefits. Environmental factors further shape outcomes. Soil pH, moisture, temperature and organic matter strongly affect inoculant establishment, with AMF faltering in alkaline or dry conditions and phosphate-solubilisers thriving in acidic, aerated soils (75). At our semi-arid site, co-inoculation excelled under mild water stress, positioning microbiomes as buffers against abiotic challenges. These synergies likely stem from cross-feeding and signalling, where bacterial acids enhance micronutrient solubility, AMF extend soil exploration and endophytes supply nitrogen networks disrupted by tillage, heavy fertilisation, or monocropping (76).

Challenges and limitations

Although encouraging results have been obtained under laboratory and controlled conditions, several constraints limit the widespread applicability of microbiome-based approaches in castor production. A major challenge is the variable performance of microbial inoculants in the field. Many strains fail to establish because they are outcompeted by native microbial populations, cannot withstand environmental stress, or are formulated with insufficient quality, leading to inconsistent outcomes between experimental trials and

real farming systems (77). Another impediment is the lack of standardised manufacturing practices and quality assurance in commercial microbial products. Differences in strain composition, carrier materials and storage conditions significantly affect inoculant effectiveness and shelf life (78). Weak and fragmented regulatory frameworks further undermine farmer confidence in bio fertiliser and bio pesticide products. While microbiome-based solutions reduce input costs in the long term, the initial investment in inoculants, training and application technologies can be prohibitive (79). Costs benefit modelling across production systems would help demonstrate economic viability and foster wider acceptance. Variations in inoculation timing, dosage, application method and co-applied fertilisers hinder comparisons across studies and obscure context-dependent success factors (80). Without robust quality control mechanisms and post-release monitoring, farmer confidence in microbiome-based products remains low, especially in resource-poor settings where failed interventions carry high costs (81). Most existing research is based on short-term studies conducted at a limited number of sites, often under controlled conditions. Consequently, the long-term durability of microbiome-mediated responses under farmer management and in the face of climate variability remains largely unknown. This variability is compounded by poor characterisation of indigenous microbial populations, limited information on soil management practices and inconsistencies in carrier materials and formulation quality (82).

Future research directions

Future research should prioritise long-term, on-farm demonstration studies that directly evaluate the persistence of microbiome-mediated benefits in castor under farmer management (83). Extended trials on marginal alfisols and vertisols, under rainfed and deficit-irrigated conditions, with and without microbial consortia, are essential to assess the durability of fertiliser reductions, yield improvements and soil organic carbon storage over time (84). A second priority is the systematic evaluation of standardised microbial consortia across diverse agro-ecological zones using harmonised experimental protocols. Such trials should incorporate core functional groups including nitrogen fixers, phosphate and potassium solubilisers, arbuscular mycorrhizal fungi and biocontrol agents and measure microbiological responses in a consistent manner (85). The integration of high-throughput sequencing with root trait phenotyping, soil moisture monitoring and process-based modelling would enable explicit quantification of microbiome impacts on water-use efficiency, nutrient cycling and stress

physiology in castor (86). Finally, cross-disciplinary efforts are needed to develop cost-effective delivery systems and decision-support mechanisms that translate microbiome technologies into farm-level realities (87). Research should also focus on developing robust carrier materials suitable for warm and dry storage conditions. Diagnostic tools for selecting appropriate microbial inoculants under specific soil and climatic conditions are also needed. Integration of microbiome management with conservation agriculture and optimised input management should be explored (88).

Implementation strategies

For microbiome-based interventions to be effective at the field scale, they must be integrated into broader agricultural management systems (89). Practices such as organic matter management, minimum tillage and crop rotation enhance microbial survival and diversity in soils, thereby improving the consistency of inoculant performance (90). Equally important is the training of farmers and extension workers. Hands-on training and field demonstrations can raise awareness of microbial technologies, while systematic knowledge dissemination facilitates adoption and uptake among farming communities (91, 92). Strong policy support and institutional cooperation are also critical. Governments and research agencies must lead efforts to incentivise sustainable practices, harmonise regulations for microbial products and fund innovations in microbiome research (93). Public-private partnerships can play a complementary role in product development, field validation and commercialisation, bridging the gap between laboratory success and field application (94).

Conclusion

Leveraging endophytic and rhizosphere microbiomes markedly boosts castor farming sustainability and climate resilience. Microbial consortia improve nutrient uptake, enhance stress tolerance, suppress pathogens and contribute to soil restoration while reducing synthetic input requirements by approximately 30-40 % without compromising yield. They enhance water-use efficiency, nutrient cycling and plant defences against climate variability. Scaling demands multidisciplinary integration of microbiome strategies with precision agronomy, standardisation and farmer training to overcome technical, economic and regulatory barriers. Continued research focusing on long-term field validation, standardised microbial formulations and effective delivery systems will be necessary for wider adoption of microbiome-based strategies in agricultural systems.

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Authors' contributions

VR conceptualised and designed the review paper, NSK supervised the article and edited the manuscript; RS made visualisation, the first draft of the manuscript was prepared and revised by NSK, VSR and SS. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors declare no conflict of interest

Ethical issues: None

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