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Biofertilizers and Organic Amendments for Enhancing Seedling Vigour in Leguminous Crops: A Review

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Abstract
Seedling vigour is an important trait for crop establishment, productivity and resilience in legume crops. Application of biofertilizers and organic amendments has been found as a sustainable approach to improve early seedling growth, germination rate and plant performance. This review summarises the recent findings on the effects of biofertilizers such as Rhizobium, Bradyrhizobium, arbuscular mycorrhizal fungi (AMF), phosphate-solubilizing bacteria (PSB) and plant growth promoting rhizobacteria (PGPR) and organic amendments like vermicompost, farmyard manure, biochar and humic acid on leguminous crop seedling vigour. Evidence indicates that the combined application of biofertilizers and organic amendments has synergistic effects that significantly improve the percentage of germination, length of seedlings, root development, vigour indices and biomass accumulation. These improvements are achieved through mechanisms of increased availability of nutrients, phytohormone production, improved soil structure, and colonisation by beneficial microbes. However, further investigation is needed on challenges such as dose optimisation, environmental variability and species-specific responses. This review emphasises the potential of integrated bio-organic strategies for sustainable legume production and identifies important knowledge gaps and future research directions.

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Keywords: seedling vigour, leguminous crops, biofertilizers, organic amendments, Rhizobium, mycorrhizae, vermicompost, germination, sustainable agriculture

Introduction
Leguminous crops are a vital component of global food security and sustainable agriculture, providing a good source of protein, fixing atmospheric nitrogen and enhancing soil fertility. Seedling vigour, characterised by fast germination, strong root growth and early biomass gain, directly affects crop stand, stress tolerance and yield potential. The environmental concerns, soil degradation and economic constraints have necessitated the need to explore sustainable alternatives to synthetic fertilisers (Mawlood, 2025) [14].

Biofertilizers and organic amendments, among the promising eco-friendly interventions, are living microorganisms that promote the availability of nutrients and plant growth and organic amendments that improve soil properties. Symbiotic relationships are established between nitrogen fixing bacteria such as Rhizobium and Bradyrhizobium and legume roots while arbuscular mycorrhizal fungi (AMF), phosphate-solubilizing bacteria (PSB) and plant growth-promoting rhizobacteria (PGPR) are involved in nutrient mobilisation and stress alleviation (Bhowmik & Das, 2018; Kumari *et al*., 2025) [6, 12]. Organic amendments such as vermicompost, farmyard manure, biochar and humic substances improve soil organic matter, water holding capacity and microbial activity (Mawlood, 2025) [14].

Recent studies suggest that combined application of biofertilizers along with organic amendments produce synergistic effects on seedling vigour than their individual applications. These integrated treatments improve the germination percentage, seedling length, root architecture, vigour indices and biomass accumulation in different leguminous crops like cowpea, mung bean, chickpea, faba bean, soybean, field pea and lentil (Asif *et al*., 2024; Iswariya & Padmavathi, 2024; Singh & Kumar, 2025) [3, 8, 28]. Different studies have been performed, but no comprehensive synthesis of the effects of biofertilizers and organic amendments on seedling vigour across legume species is available. This review aims to fill this void by reviewing the current evidence and identifying priorities for future research.

Biofertilizers and Legume Seedling Vigour

Rhizobium and Bradyrhizobium Inoculation

Rhizobium and Bradyrhizobium species are well-studied biofertilizers for leguminous crops due to their symbiotic nitrogen-fixation ability. These bacteria make special nodules on roots where they change nitrogen from the air into ammonia, a natural source of nitrogen for plants to grow. Inoculating the seed increases nodulation, nitrogen availability and early seedling establishment. The research on lentil revealed that Rhizobium inoculation with sludge ash as carrier material improved nodulation and significantly higher germination rate than conventional carriers (Paliya *et al*., 2019) [18]. This novel carrier approach emphasises the significance of carrier selection in the biofertilizer efficacy.
Inoculation of Faba bean with specific strains of Rhizobium (FB-WAR-15, TAL-1035, EAL-110) resulted in better growth parameters, with strain EAL-110 achieving a 22.3% increase in nodule dry weight when combined with biochar application (Tadesse *et al*., 2024) [32]. According to Praveen *et al*. (2022) [19] Rhizobium primed chickpea seeds recorded 90 per cent field emergence and improved growth and yield attributes. In soybean, Bradyrhizobium japonicum inoculation increased shoot biomass by 27% in green manure amended soils and 45% in farmyard manure amended systems, highlighting the significance of organic matter for bacterial efficacy (Javaid & Mahmood, 2010) [9]. The strain-specific responses highlight the need to select suitable rhizobial strains for particular legume species and environmental conditions (Sufar *et al*., 2024) [30].

Arbuscular Mycorrhizal Fungi

Arbuscular mycorrhizal fungi establish mutualistic associations with legume roots, enhancing root surface area and improving nutrient uptake, particularly phosphorus. These fungi form arbuscules in root cortical cells, through which nutrients can flow in both directions between plant and fungus. The extensive hyphal networks reach beyond the zone of nutrient depletion around roots, extending to soil resources unavailable to non-mycorrhizal plants. Combination of VA-mycorrhizal inoculation with Bradyrhizobium and chicken manure significantly improved seedling vigour and early growth attributes in faba bean. This triple interaction shows the potential to combine several beneficial microorganisms with organic amendments. Cowpea integrated mycorrhizal inoculation (Mycoroot™) with biochar-compost mixtures boosted germination, nodulation and growth under drought stress conditions. The stress-relieving effects of mycorrhizae are especially beneficial in water-limited environments where seedling establishment is difficult. The seedling studies showed highest growth and vigour when VAM was inoculated at 10 mL per plant with shoot length 32.04 cm at 90 days and 38.38 cm at 180 days, which was significantly higher than other biofertilizer treatments (Saini *et al*., 2024) [22]. Seedlings quality index under VAM treatment (0.78) was significantly higher than controls indicating an overall improvement in seedling performance. Legumes with mycorrhizae benefit from improved phosphorus uptake, improved water relations, higher resistance to soil-borne pathogens and improved soil structure through hyphal binding of soil particles (Havugimana *et al*., 2016) [7]

Plant Growth-Promoting Rhizobacteria

Plant growth-promoting rhizobacteria (PGPR) include diverse bacterial genera such as Pseudomonas, Bacillus and Azospirillum which promote plant growth by various mechanisms besides nitrogen fixation. These mechanisms include phosphate solubilisation, siderophore production for iron acquisition, synthesis of plant growth hormones, production of antibiotics against phytopathogens and induction of systemic resistance in plants. In cowpea, Pseudomonas fluorescens treatment at 5% concentration for eight hours resulted in high seedling vigour values and was next only to humic acid treatment (Iswariya & Padmavathi, 2024) [8].
The white lupine treated with PGPB-enriched organic fertiliser containing Bacillus pretiosus and Pseudomonas agronomica recorded dramatic increases of 70–88% in shoot weight, about 80% in total biomass, and up to 36% in shoot elongation compared to controls (Robas-Mora *et al*., 2025) [21]. The multi-strain bacterial consortia showed better performance than the single-strain inoculants, most likely because of complementary mechanisms of action and functional redundancy (Miranda, 2023) [15]. In peanut, a biofertilizer with 25% concentration of Bradyrhizobium sp., Azospirillum brasilense, Bacillus subtilis, Pseudomonas fluorescens and Trichoderma atroviride resulted in the best germination and germination speed index (Bacha *et al*., 2023) [5]. These results suggest the potential of PGPR to improve the seedling vigour through the production of phytohormones, siderophores and antagonism to phytopathogen (Swarnalakshmi *et al*., 2020) [31].

Phosphate-Solubilizing Bacteria

Phosphate-solubilizing bacteria (PSB) transform insoluble inorganic phosphate compounds to plant-available orthophosphate and thus enhance phosphorus nutrition important for seedling development. PSB secrete organic acids that can solubilise mineral phosphate in the soil and make it available to plants. The role of PSB and organic amendments in chickpea cultivation has been observed to cause significant improvement in early seedling establishment by improving phosphorus availability. The combination of PSB and rhizobia enhances phosphorus availability and increases growth of forage legumes suggesting a synergistic effect between biofertilizer components (Ríos-Ruiz *et al*., 2024) [20].

Organic Amendments and Seedling Vigour

Vermicompost and Farmyard Manure

Vermicompost and farmyard manure are common organic amendments used for improving soil fertility, structure and biological activity. Vermicompost is a rich source of organic matter processed by earthworms and contains plant-available nutrients, favourable microorganisms and humic substances. Seed priming of chickpea with vermiwash (10% concentration) for 12 hours resulted in 90% field emergence and overall better growth performance (Praveen *et al*., 2022) [19]. Farmyard manure, vermicompost, poultry manure and Jeevamrutha were effective when used with Rhizobium and PSB biofertilizers in improving nodulation and yield performance in mung bean (Kalson *et al*., 2024) [10].

Comparative studies have shown different organic amendments to have differential effects on seedling parameters. Maximum seedling quality index was recorded in vermicompost @ 2:1 ratio with red soil whereas farmyard manure helped in early seedling establishment (Saini *et al*., 2024) [22]. Application of compost and vermicompost substantially increased growth, yield and nutrient content in common beans (Al-Tawarah *et al*., 2024) [1]. Bio-organic amendments enhanced faba bean productivity and nutrient uptake in acid soils, emphasising the significance of soil pH to mediate the effect of amendments (Tadesse *et al*., 2024) [32].

Biochar Applications

Pyrolysis of organic materials in an oxygen-limited environment produces biochar, which has garnered attention for its ability to improve soil properties and enhance nutrient retention. Its porous structure and high surface area provides habitat for beneficial microorganisms and improves water and nutrient retention. Soybean treated with 2.5% cow dung and 2.5% biochar combined with synthetic fertiliser resulted in significantly higher initial relative growth rate, number of leaflets, root dry weight and shoot dry weight (Samarakoon & Yapa, 2017) [23]. The application of coffee husk biochar at 10 t ha^{-1} in conjunction with Rhizobium strain EAL-110 significantly improved growth, nodulation and nutrient uptake of faba bean (Tadesse *et al*., 2024) [32].

The combination of biochar and mycorrhizal inoculation has shown synergistic effects on seedling performance. Biochar-compost mixtures combined with Mycoroot™ inoculation applied to cowpea improved germination and growth under drought stress conditions, indicating the ability of biochar's water retention properties to complement the stress-mitigating effects of mycorrhizal colonisation. The combined effect of biochar and bio-fertilizer enhances cowpea yield and yield components under water-deficit stress (Moosavi *et al*., 2020) [17]. In mung bean, seed coating formulations with biochar and NPK-solubilizing PGPR and zinc oxide nanoparticles were found significantly better than other treatments and showed strong association with vigour indices, germination percentage and seedling biomass (Singh & Kumar, 2025) [28].

Humic Substances and Liquid Organic Fertilizers

Humic substances (humic and fulvic acids) are biostimulants that enhance nutrient uptake, root growth, and stress tolerance. Among all the biostimulants tested, the highest seedling vigour was obtained with humic acid at a 5% concentration for eight hours in cowpea showing the superior biostimulant effect of humic substances (Iswariya & Padmavathi, 2024) [8]. Compost and humic acid amendments are a practicable solution to rehabilitate weak arid soil for higher winter field pea production (Sher *et al*., 2023) [25].

Liquid organic fertilisers showed variable effects depending on their composition and concentration. The best results were obtained with the application of Humate K^+ and Probio Fert, which favoured a greater development of roots in bean seedlings (Maestre *et al*., 2024) [13]. However, higher doses of bioinputs were not guarantyd to improve and may lead to deleterious effects, especially in soybean, highlighting the need to optimise the dose. Seed treatments with biological control agents and liquid organic fertilisers improved germination, shoot length and vigour index in mung bean, suggesting that biological inputs can effectively replace or supplement traditional organic amendments (Kumari *et al*., 2025) [12].

Combined Effects of Biofertilizers and Organic Amendments

The combined application of biofertilizer and organic amendments showed always a synergistic effect higher than the benefits of each of the applications alone in different legume species. The co-application of bacterial consortia with organic amendments in mash bean significantly enhanced the growth and seed quality showing the complementing effect of biological and organic inputs (Asif *et al*., 2024) [3]. Field pea studies revealed that the combined inoculation with organic manure resulted in better seedling dry weight and vigour index. In French bean, seed germination and seedling vigour were improved by carrier based biofertilizers in combination with farmyard manure, green manure and vermicompost.

Some specific combinations were found to be very effective. In soybean, Bradyrhizobium japonicum with farmyard manure increased shoot biomass by 45% and with green manure, the same biofertilizer increased shoot biomass by 27% (Javaid and Mahmood, 2010) [9]. The three-way interaction of faba bean variety, Rhizobium strain and biochar had significant effect on nodule dry weight and overall seedling performance (Tadesse *et al*., 2025) [33]. Multi-component formulations are a sophisticated approach: seed coating with biochar combined with NPK-solubilising PGPR and zinc oxide nanoparticles showed significant superiority over simpler treatments in mung bean (Singh & Kumar, 2025) [28]. Robas-Mora *et al*. (2025) [21] reported increases of 70–88% in shoot weight and about 80% in total biomass of white lupine when using PGPB-enriched organic fertiliser derived from horticultural waste.

The role of biofertilizers to pulse crops has evolved from single-strain inoculants to sophisticated microbiome-based approaches using complex microbial community interactions (Xavier *et al*., 2023) [34]. Species-dependent PGPR co-inoculation effects in legume plants as revealed by global meta-analysis emphasise the requirement of crop-specific inoculant selection (Silva *et al*., 2024) [26]. Synergistic effect of PGP agents and Rhizobium spp. reported for improved plant growth, nutrient mobilisation and yields in diverse leguminous crops (Babu *et al*., 2015) [4].

Mechanisms of Action

Nutrient Mobilization and Availability

Biofertilizers and organic amendments improve seedling vigour through improved mobilisation of nutrients during critical stages of early growth. The bacteria Rhizobium and Bradyrhizobium begin nitrogen fixation after the formation of nodules, which provides available nitrogen for developing seedlings (Shahrajabian *et al*., 2021; Sufar *et al*., 2024) [24, 30]. Phosphate-solubilizing bacteria convert inorganic phosphate into forms that can be taken up by plants, improving the uptake of phosphorus, which is essential to root development (Ríos-Ruiz *et al*., 2024) [20]. Arbuscular mycorrhizal fungi increase effective root surface area and the uptake of phosphorus and micronutrients (Havugimana *et al*., 2016) [7]. Organic amendments contribute to nutrient mobilisation via different pathways. Vermicompost and farmyard manure supply slow-release nutrients and improve cation exchange capacity and soil microbial biomass (Al-Tawarah *et al*., 2024) [1]. Biochar is porous and thus improves the retention of nutrients and reduces leaching losses, while providing a habitat for microorganisms involved in nutrient cycling (Moosavi *et al*., 2020) [17]. Humic substances chelate micronutrients and form stable complexes with soil minerals, thus enhancing their solubility and uptake by developing seedlings (Sher *et al*., 2023) [25].

Phytohormone Production

The production of phytohormones (i.e. auxins, cytokinins and gibberellins) by plant growth promoting rhizobacteria and their effect on seedling growth. Pseudomonas and Bacillus species produce indole-3-acetic acid (IAA) that stimulates root elongation and lateral root formation, enhancing the water and nutrient uptake capacity of developing seedlings (Babu *et al*., 2015; Khan *et al*., 2017) [4, 11]. Cytokinins stimulate cell division and shoot development and gibberellins promote germination and seedling elongation (Miranda, 2023) [15]. Growth-promoting substances may be present in, or generated by, organic amendments. Naturally occurring plant growth regulators found in vermiwash and liquid organic fertilisers stimulate germination and early development (Soniya *et al*., 2022) [29].

Soil Physical and Biological Properties

Organic amendments improve soil physical properties which have a direct effect on seedling emergence and establishment. Vermicompost, farmyard manure and biochar improve soil structure, porosity and water holding capacity favouring the conditions for germination and root penetration. Better aeration helps with root respiration and microbial activity, and better water retention ensures adequate moisture during critical growth phases (Mawlood, 2025) [14]. Biofertilizers and organic amendments enhance soil biological properties in a synergistic manner by increasing microbial biomass, diversity and activity. Organic matter provides energy and carbon sources for beneficial microorganisms, fostering strong microbial communities that contribute to seedling establishment (Robas-Mora *et al*., 2025) [21]. Beneficial microbial communities antagonise and compete with soil-borne pathogens, hence reducing seedling diseases and improving establishment (Singh & Kumar, 2025) [28].

Stress Tolerance Enhancement

Biofertilizers and organic amendments improve the seedling stress tolerance by multiple mechanisms. Mycorrhizal colonisation enhances water uptake and induces physiological acclimations (e.g. changes in stomatal conductance and osmotic adjustment) that improve drought tolerance. ACC deaminase produced by PGPR reduces the ethylene level under stress maintaining normal growth and development under adverse conditions (Swarnalakshmi *et al*., 2020) [31]. Organic amendments improve the soil buffering capacity and reduce the impacts of salinity, acidity and other chemical stresses (Tadesse *et al*., 2024; Tadesse *et al*., 2025) [32, 33]. Complete stress protection in the vulnerable early growth stages is available with combined applications. Rhizobium inoculation combined with coffee husk biochar improved faba bean productivity in acidic soils by ameliorating soil pH and enhancing nutrient availability (Tadesse *et al*., 2024, 2025) [32, 33]. Inoculating mycorrhizae with biochar-compost mixtures improved water relations and reduced osmotic stress, which enhanced cowpea germination and growth under drought conditions. Rhizobium, Bradyrhizobium and other nitrogen-fixing bacteria have a significant contribution to sustainable agricultural production and play a role in maintaining the health of seedlings under both optimal and stress conditions (Shahrajabian *et al*., 2021) [24].

Challenges and Future Perspectives

Dose-Response Relationships

Optimisation of application rates is critical to maximise seedling vigour and avoid deleterious effects. However, research has shown that excessive doses of bioinputs do not guarantee improvements and can cause harmful effects, especially in sensitive legume species such as soybean (Maestre *et al*., 2024) [13]. The optimal concentration of biostimulants varies among legume species. Cowpea showed the best response at 5% humic acid, but other species may require different concentrations and durations of treatment (Iswariya & Padmavathi, 2024) [8]. The effectiveness of seed priming is dependent on its duration, with 8–12 hour treatments being the most effective (Iswariya & Padmavathi, 2024; Praveen *et al*., 2022) [8, 19].

Environmental and Genotypic Interactions

The effectiveness of biophertilizer and organic amendment is highly dependent on the environments and crop genotypes. The faba bean varieties responded differently to the Rhizobium strains and biochar application, with the Dosha variety being particularly strong in response (Tadesse *et al*., 2024) [32]. Environmental factors like temperature, moisture and soil properties influence microbial survival and efficiency. The results of studies on legume germination indicate that the optimal temperature range for germination is 25°C to 34°C, while temperatures below 18°C reduce germinative power. Therefore, the application of biofertilizers should be adapted to the prevalent environmental conditions (Bacha *et al*., 2023) [5]. The effect of PGPR co-inoculation in legume plants was species-dependent, which suggests the need for genotype-specific recommendations (Silva *et al*., 2024) [26].

Carrier Materials and Application Methods

Development of efficient carrier materials and application methods are crucial to improve the performances and shelf-life of biofertilizers. Sludge ash has been found to be a good carrier for Rhizobium in place of the commonly used peat-based carrier and improves nodulation and germination in lentil (Paliya *et al*., 2019) [18]. Seed coating formulations involving multiple components such as biochar, PGPR and nanoparticles provide promising delivery approaches that can ensure intimate contact between microorganisms and germinating seeds (Singh & Kumar, 2025) [28]. Biofertilizer technology has expanded from single-strain inoculants to microbiome-based technologies, providing better delivery systems and increased efficacy in diverse environments (Anbarasan *et al*., 2024) [2]. The benefits of synergistic effects can be obtained by combining seed treatment and soil application, which allows for instant colonisation of seedlings and maintenance of microbial populations throughout the crop cycle (Praveen *et al*., 2022; Soniya *et al*., 2022) [19, 29].

Research Gaps and Opportunities

Although there have been considerable advances, there are still several important knowledge gaps regarding the effects of biofertilizers and organic amendments on seedling vigour. Molecular mechanisms controlling plant-microbe interactions during early seedling establishment remain to be further elucidated. The role of microbial community interactions, including synergistic and antagonistic interactions among co-inoculated organisms, should be systematically investigated (Xavier *et al*., 2023; Silva *et al*., 2024) [34, 26]. A priority in emerging research is the possible impact of climate change on biofertilizer efficacy. Microbial survival and plant-microbe interactions could be affected by increasing temperatures, precipitation changes, and extreme weather events.

The convergence of advanced technologies such as genomics, metabolomics, and precision agriculture provides opportunities for the development of next-generation biofertilizers with enhanced efficacy and reliability (Anbarasan *et al*., 2024) [2]. The co-inoculation of rhizobia and other plant growth-promoting rhizobacteria as biofertilizers is a biotechnological frontier with great potential to improve the vigour of legume seedlings in different agricultural systems (Miranda, 2023) [15]. The trajectory of innovation in this field is exemplified by the contribution of biofertilizers to pulse crops, from single-strain inoculants to microbiome-based strategies (Xavier *et al*., 2023).

Conclusion

The present review shows that biofertilizers and organic amendments greatly improve the seedling vigour of leguminous crops through complementary and synergistic mechanisms. Evidence consistently supports the superiority of combined bio-organic approaches over individual applications across various legume species and environmental conditions. Rhizobium, Bradyrhizobium, AMF, PSB and PGPR have their own mechanisms but when combined with the right organic amendments they show enhanced performance.

Vermicompost, farmyard manure, biochar, and humic substances improve the soil condition for microbial efficacy and provide direct nutrient and biostimulant benefits to growing seedlings. The application of such biological and organic inputs in holistic schemes of soil management provides a pathway for sustainable legume production that reduces reliance on synthetic fertilisers, while maintaining or improving crop productivity.

Future research should be directed toward optimisation of application rates and combinations for specific legume species and environments, development of improved carrier materials and formulations, investigation of molecular mechanisms and evaluation under projected climate scenarios. Adoption of integrated bio-organic approaches is a major step in the direction of achieving sustainable intensification of legume production systems that satisfy food security needs while maintaining environmental health.

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