Sustainable Soil Enrichment in Forest Farming: Role of Microbial Biofertilizers and Biostimulants

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ABSTRACT

Forest farming, a form of agroforestry, is a sustainable agricultural practice that integrates trees with other high-value crops. Sustainable soil enrichment is essential for the success of forest farming, where ensuring both productivity and ecological balance depends on the complex interactions between plants and diverse soil microbial communities. The use of microbial biofertilizers and biostimulants offers a sustainable, eco-friendly strategy to enhance soil health and stimulate plant growth by improving nutrient availability, strengthening tolerance to biotic and abiotic stresses, and reducing dependence on synthetic chemicals. Biofertilizers including nitrogen fixing bacteria, phosphate- and potassium-solubilizing microbes, and mycorrhizal fungi play a key role in nutrient cycling. Furthermore, the microbes or microbial consortia involved in organic matter decomposition and carbon sequestration contribute to improving soil health and formation of beneficial soil structures. Likewise, biostimulants such as microbial consortia, protein-based compounds, compost, and humic substances enhance soil microbial activity, encourage root development, and improve overall plant vigor. Incorporating these biological amendments

into forest farming promotes long-term soil fertility, fosters biodiversity, and strengthens ecosystem services such as carbon sequestration and water retention. This strategy supports sustainable land management, providing an effective means to boost productivity while safeguarding the integrity of forest ecosystem. This article highlights the role of different microbes in forest farming and the effect of application of different biofertlizers and biostimulants on growth and development of various tree crops under normal as well stress conditions.

INTRODUCTION

Forest farming, a form of agroforestry that integrates the cultivation of high-value crops that involves the intentional production of non-timber forest products (NTFPs) under a forest canopy, is increasingly recognized for its potential to promote biodiversity, enhance ecosystem services, and support sustainable livelihoods. However, maintaining soil fertility and productivity in such systems without degrading the forest environment presents a unique challenge. External inputs like as mechanical site preparation, irrigation, and fertilization are considered critical for the effective production of tree crops. Conventional chemical inputs can disrupt forest soil ecology, leach into water systems, and reduce long-term sustainability. These human activities have resulted in constant soil erosion, generating crucial nutrient deficits in forest soils. Nutrient management plays a crucial role in sustaining plant productivity while ensuring ecological and social responsibility. Microbial biofertilizers consist of beneficial microorganisms such as nitrogen-fixing bacteria, phosphate and potassium solubilizing microbes, and mycorrhizal fungi that enhance nutrient availability and uptake by plants. Biostimulants comprising mixtures of polypeptides, oligopeptides, amino acids, or beneficial microorganisms are commonly applied in nursery settings to encourage seedling development, either through root application, soil drenching, or foliar spraying (Ozyhar *et al*., 2019). It promotes plant growth by improving root architecture, enhancing stress tolerance, and stimulating microbial activity in the rhizosphere. These substances are applied directly to tree plants or used to treat seedlings, aiming to enhance nutrient uptake, improve tolerance to abiotic stresses, boost crop quality, maintain soil structure, improve organic matter content, and support diverse microbial communities essential for nutrient cycling and plant health.

Preserving ecosystem functionality, particularly within forest ecosystems, requires the restoration of soil's physical, chemical, and biological properties. In these systems, nutrient cycling through litter decomposition plays a vital role in transferring nutrients to the soil, thereby enhancing soil fertility, promoting microbial activity, and supporting plant growth. Soil microorganisms are central to this process, driving nutrient transformation and release through various soil functions. Maintaining this below-ground microbial diversity is essential for sustaining overall forest health. In this context, microbial biofertilizers and biostimulants emerge as eco-friendly alternatives that align with the principles of sustainable land management. This article investigates how microbial biofertilizers and biostimulants contribute to improving soil health in forest farming systems (Khan *et al*., 2015; Ozyhar *et al*., 2019; Chaiya *et al*., 2021). It delves into the functional mechanisms of these microbial inputs, their suitability for various forest crops,

and their capacity to lessen reliance on chemical fertilizers while promoting long-term soil fertility and strengthening ecological sustainability.

Role of microbes in forest farming

Microorganisms play a fundamental role in maintaining soil health and supporting plant productivity in forest farming systems. These microbes including bacteria, fungi, actinomycetes, and cyanobacteria are essential for nutrient cycling, organic matter decomposition, and the formation of beneficial soil structures. To stimulate tree plant growth, nutrient uptake (nitrogen (N), phosphorus (P), potassium (K), iron (Fe), zinc (Zn), and sulphur (S)), and resistance to various abiotic stresses, these can be applied to plants or seedlings through more than one method, either concurrently or at different times under different conditions.

Forest trees are fully reliant on a symbiotic relationship between their roots and soil microbes, particularly ectomycorrhizal fungi. Minerals are mobilized from the soil and transferred to the plant by this fungus. In exchange, the trees provide the fungi with absorbed carbon. An ectomycorrhizal fungus can link to and integrate the roots of multiple trees, allowing the fungus and roots to develop together as a single entity (Chaiya *et al*., 2021). Basidiomycetes make up the majority of ectomycorrhizal fungi, with *Amanita*, *Cortinarius*, *Lactarius*, *Russula*, and *Suillus* among the most well-known. When it was discovered that trees often fail to grow at new places if the ectomycorrhizal symbiont is absent, the importance of ectomycorrhiza in forest plantations garnered a lot of attention. One such example is in Western Australia, *Pinus radiata* and *P. pinaster* failed to develop in nursery beds due to a lack of mycorrhizal fungi. Even fertilizer had no influence on the establishment of seedlings on these sites or their ability to boost nitrogen absorption and usage.

Biostimulants in the form of biofertilizers or amino acid/protein-based chemicals are more well-known and used in agriculture, but their utility in tree crops is still in the experimental stage. The use of various biostimulating compounds or microorganisms in agroforestry could be a viable sustainable technique for enhancing tree crop growth, development at the nursery stage, as well as in the forest ecosystem (Almadi *et al*., 2020). The application of different biofertlizers and biostimulants on various tree crops are given in the Table 1.

Table 1: Examples of use of biofertilizers and biostimulants in improving tree growth, nutrient uptake, and stress resilience

Tree/seedlings	Biostimulants used	Condition	Benefits	Reference
Silver Oak	*Trichoderma*, P-solubilizer and N fixer	Normal	Improved growth and biomass of seedling	Umashankar *et al*. (2012)
Douglas-fir	Diazotrophic endophytic consortia	Normal	Seedling plumule and radicle length and biomass was improved	Khan *et al*. (2015)
Japanese persimmon	Calcium protein hydrolysates	Salinity stress	Increased the concentration of compatible solutes	Visconti *et al*. (2015)
Monterey pine	Aerated compost tea (ACT)	Normal	Improved root architecture, photosynthetic pigments and K content	Otero *et al*. (2019)
Southern blue	Amino acid containing	Normal	Improved biomass	Ozyhar *et al*.

gum tree	protein hydrolysate		accumulation, increased photosynthetic activity and growth	(2019)
Olive tree	Biostimulant (dry yeast suspension, amino acid, sea weed extract and protein hydrolysates)	Normal	Improved yield, fruit characteristics, plant biomass and oil quality	Almadi *et al.* (2020)
Teak	Nitrogen-fixer, actinobacterium-*Kitasatospora* sp. and AMF	Normal	Increased teak seedling biomass, Improved N and P uptake	Chaiya *et al.* (2021)
Chestnut	Biostimulant (*Azospirillum*, *Frankia*, AM fungi, Phosphobacteria)	Water deficit stress	Better quality and growth of seedlings	Fuertes-Mendizabal *et al.* (2021)

CONCLUSION

Microbial biofertilizers and biostimulants hold immense potential in promoting sustainable soil enrichment within forest farming systems by enhancing nutrient cycling, improving soil structure, and supporting plant-microbe symbiosis. Their application reduces dependence on synthetic inputs and minimizes environmental degradation. Moving forward, integrating these microbial solutions with site-specific management practices can further amplify their effectiveness, making them vital tools in advancing sustainable forest agriculture.

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