

MICROBIOME ENGINEERING FOR SUSTAINABLE FRUIT CROP PRODUCTION IN INDIA: 4F BIOECONOMY MODEL

Sharmistha Basu

Assistant Professor, Department of Botany, Victoria Institution (College), 78-B A.P.C. Road, Kolkata 700009, West Bengal

ABSTRACT

One of the greatest challenges of Indian fruit production is meeting rising demand while reducing dependence on synthetic fertilizers and pesticides. Plant- and soil-associated microbiomes are now recognized as one of the important agents for improving soil health and fruit quality by enabling nutrient cycling, improving stress tolerance and helping in biological disease control (Nadarajah & Rahman, 2023; Kaul et al., 2021; Suman et al., 2022; Srivastava et al., 2021). A “designer” rhizosphere and phyllosphere communities that enhance productivity under biotic and abiotic stresses is offered by Microbiome Engineering—through targeted use of microbial consortia, host-mediated selection, and in situ manipulation (Nadarajah & Rahman, 2023; Kumar & Dubey, 2020; Mahmud et al., 2021; Kaul et al., 2021; Afridi et al., 2022).

The present paper highlights the latest concepts and tools in the plant microbiome engineering and incorporates them with fruit production systems in Indian context, emphasizing the importance of Integrated Soil Fertility Management (ISFM), organic and biofertilizer-based horticulture, and emerging “microbiome-driven cropping systems (Nadarajah & Rahman, 2023; Srivastava et al., 2021). The chapter synthesizes the mode 4 approach centred on (i) study of native fruit crop microbiomes, (ii) integrating beneficial microbes with in sustainable agricultural systems, (iii) co-optimization of host- microbe using omics and gene editing and (iv) farmer acceptable and accessible technology. Further, the chapter concludes with the research and policy priorities to mainstream microbiome engineering in climate-smart, resource-efficient Indian fruit production

KEYWORDS: *Plant Microbiome; Microbiome Engineering; Rhizosphere; Fruit Crops; India; Biofertilizers; Biocontrol; Integrated Soil Fertility Management (ISFM); Sustainable Horticulture; Omics; CRISPR; Mode 4 Agriculture.*

Article History

Received: 24 Dec 2023 | Revised: 27 Dec 2023 | Accepted: 31 Dec 2023

INTRODUCTION

Plant and soil microbiome are the complex communities which are crucial for plant health, nitrogen fixation, phosphorus solubilisation, disease resistance, and stress tolerance against pathogens and drought (Suman et al., 2022). Microbiome engineering involves the targeted manipulation, modification and design of microbial communities to improve plant health, yield, resilience and agriculture, and ecosystem function (Nadarajah & Rahman, 2023; Kaul et al., 2021; Bano et al., 2021; Qiu et al., 2019).

Traditional tools like Biofertilizers or Biopesticides, often show unpredictable performance in farmers' fields due to their nature as living organisms making them extremely sensitive to soil characteristics, environmental conditions, and application methods (Nadarajah & Rahman, 2023; Mahmud et al., 2021; O'Callaghan et al., 2022; Batista & Singh, 2021).

Recent advances in next – generation omics have facilitated detailed characterisation of plant-associated microbiomes and generated new avenues for rational design of synthetic communities and host-mediated microbiome selection (Nadarajah & Rahman, 2023; Kumar & Dubey, 2020; Kaul et al., 2021; Thakur et al., 2023; Trivedi et al., 2021).

MICROBIOMES IN FRUIT-BASED PRODUCTION SYSTEMS

Climate-smart agriculture in India is boosted by Integrating perennial horticulture and fruit trees by sequestering carbon and restoring soil which involves Integrated Soil Fertility Management (ISFM) where organic inputs, inorganic fertilizers, and microbial inoculants (consortia) simultaneously improve yields, soil organic carbon, microbial activity, and nutrient-use efficiency (Srivastava et al., 2021). Many research reports from India, Iran, and China point towards the fact that ISFM with rhizosphere-specific microbial consortia enhances fruit productivity and soil health, close to climate-resilient nutrient management (Srivastava et al., 2021). Ecofriendly organic and bio-input management for Indian fruit and horticultural crop production using composts, vermicompost, green manures, Azospirillum, Rhizobium, phosphate-solubilizing bacteria, and mycorrhizae significantly increases the soil biological activity, water retention, and fruit nutritional quality, like increased vitamin C and antioxidants in mango, guava, pomegranate, citrus, papaya (Bhardwaj et al., 2010; Dutta & Kundu, 2012).

MECHANISMS OF MICROBIOME-MEDIATED BENEFITS IN FRUIT CROPS

Beneficial plant-associated microbes contribute to fruit crop performance through multiple mechanisms:

- **Nutrient cycling and biofertilization:** Microbes transform insoluble mineral substrates into bioavailable nutrients through acidolysis, chelation, and the production of organic acids like Phosphate-solubilizing bacteria (PSB) and fungi (*Trichoderma*) using acid phosphatase (ACP) enzymes. Many bacteria, like *Bacillus* and *Pseudomonas*, produce siderophores—that sequester ferric iron (Fe^{3+}) thereby making it available to the plant while depriving pathogens of this essential resource. Microbial communities perform biological nitrogen fixation (BNF) which converts atmospheric nitrogen which plants cannot use directly, into bioavailable forms like ammonia. *Rhizobium*, *Azotobacter*, *Bradyrhizobium*, and *Azospirillum* are central to this process (Kumar & Dubey, 2020; Suman et al., 2022).
- **Phytohormone and metabolite production:** Rhizobacteria and endophytes produce auxins, gibberellins, cytokinins, and siderophores that stimulate root growth and improve iron acquisition (Kumar & Dubey, 2020; Suman et al., 2022).
- **Stress tolerance and climate resilience:** Microbiome are can effectively enhance drought and salinity tolerance through osmolyte production, induced systemic tolerance and improved water-use efficiency (Kaul et al., 2021; Thakur et al., 2023; Afridi et al., 2022).
- **Biocontrol of pests and diseases:** Through various mechanisms like competition, antibiosis, parasitism, rhizosphere and phyllosphere microbes suppress pathogen and triggers host defence pathways (Nadarajah & Rahman, 2023; Mahmud et al., 2021; Batista & Singh, 2021)

- **Soil health and structure:** Soil microbes physically construct soil structure by using fungal hyphae to weave particles together and secreting "biological glues" like glomalin and bacterial films to cement the soil particles into stable, erosion-resistant aggregates. Also, they help in carbon sequestration and ensure long-term soil fertility, which are vital for perennial fruit orchards (Nadarajah & Rahman, 2023; Srivastava et al., 2021; Suman et al., 2022; Singh et al., 2020).

In horticulture, microbial Biocontrol Agents (BCAs)—predators, parasitoids, or microorganisms—are used to manage pests and diseases (*Trichoderma*, *Bacillus*, *Pseudomonas*, entomopathogenic fungi, and others). These are sustainable and ecofriendly alternatives to pesticides, with genetic engineering being explored to enhance their efficacy and persistence (Rahman et al., 2018; Mon et al., 2021; Sharma et al., 2023; Adedayo et al., 2022).

TOOLS AND STRATEGIES FOR MICROBIOME ENGINEERING

Microbial Inoculants and Synthetic Consortia

Instead of single-strain inoculants, modern microbiome engineering focuses on indigenous consortia and synthetic communities customised to specific crops, soils, and climatic conditions (Mahmud et al., 2021; Singh et al., 2020; Qiu et al., 2019; Batista & Singh, 2021). Integrated Soil Fertility Management (ISFM) in fruit crops relies on consortium-based biofertilizers in combination with organic and inorganic inputs (Srivastava et al., 2021).

However, poor establishment, competition with native microbiota and environmental variability are the major hurdles in inoculant performance (Nadarajah & Rahman, 2023; Mahmud et al., 2021; O'Callaghan et al., 2022; Batista & Singh, 2021). Emerging strategies to improve success include:

- It is desirable to select the strains which are well adapted to local climate and local soil, particularly from high performing rhizosphere (Mahmud et al., 2021; Singh et al., 2020; Qiu et al., 2019).
- To enhance survival and colonization, it is important to optimize the formulation and delivery mechanisms (coating, encapsulation, carriers) (Singh et al., 2020; O'Callaghan et al., 2022).
- Designing microbial consortia by integrating strains with synergistic functions—such as nitrogen fixation, phosphate solubilisation and pathogen defense—while incorporating functional redundancy to improve ecosystem stability and resilience (Mahmud et al., 2021; Singh et al., 2020; Qiu et al., 2019; Batista & Singh, 2021).

In Situ Microbiome Manipulation

Instead of introducing exogenous strains, in situ microbiome engineering focuses on modification of microbial communities indirectly through management practices and prebiotic amendments (Singh et al., 2020; Bano et al., 2021; Trivedi et al., 2021).

Approaches include:

- Biofertilization and Reduced tillage for maintaining a stable functional rhizosphere microbiome (Bano et al., 2021).
- Organic amendments- Adding composts, green manures, cover crops, biochar provides a carbon source that favour beneficial microbes and enhance microbial diversity (Srivastava et al., 2021; Suman et al., 2022).

- Targeted “prebiotics” to favour beneficial groups like Plant Growth-Promoting Rhizobacteria (PGPR) or Arbuscular Mycorrhizal Fungi (AMF). (Singh et al., 2020; Batista & Singh, 2021).

These strategies are with too high input costs for smallholder Indian fruit systems with limited land and resources, where Government rules and approvals can make it difficult to use high tech technologies (Alam et al., 2023).

Host-Mediated Microbiome Engineering

Plant genetic factors regulate the host mediated strategies for microbial recruitment and involves the plant genetic factors which controls the rhizosphere composition by activation of immune signalling and secretion of root exudates (Kumar & Dubey, 2020; Kaul et al., 2021; Trivedi et al., 2021). Various Host- Mediated strategies are as follows:

- Selecting those fruit cultivars or breeds which stimulates the growth of beneficial microbiomes (e.g., microbiome-shaping “M genes”) (Kaul et al., 2021).
- Genome editing tools like CRISPR/Cas can effectively modify host genes, affecting microbiome composition and stress responses (Nadarajah & Rahman, 2023; Kumar & Dubey, 2020; Kaul et al., 2021; Thakur et al., 2023; Bano et al., 2021).
- Using various genetic engineering techniques or coating the seed coat with desired bacterial communities, the seed microbiome can be manipulated (Kumar & Dubey, 2020; Afridi et al., 2022; Qiu et al., 2019).

These approaches increase fruit production by enhancing plant nutrient uptake, increased disease resistance, boosting stress tolerance against drought and salinity. Hence, creating a “-optimised crops” (Kaul et al., 2021; Trivedi et al., 2021; Rahman et al., 2018).

Multi-Omics, Data Integration, and Predictive Ecology

Metagenomics, metatranscriptomics, metaproteomics, and metabolomics facilitates development of tailored fruit crop microbiomes across rhizosphere, endosphere, and phyllosphere (Nadarajah & Rahman, 2023; Kaul et al., 2021; Thakur et al., 2023; Afridi et al., 2022; Trivedi et al., 2021). following supports are offered by Integrated multi-omics and computational modelling:

- Pinpointing the core and keystone taxa responsible for high yield, quality, or resilience (Nadarajah & Rahman, 2023; Suman et al., 2022; Singh et al., 2020; Trivedi et al., 2021).
- Understanding of metabolic exchanges and signalling networks governing plant–microbe and microbe–microbe interactions (Nadarajah & Rahman, 2023; Kaul et al., 2021).
- Data driven engineering of beneficial microbial consortia and customized economic strategies for specialized agricultural zones (Kaul et al., 2021; Singh et al., 2020; Bano et al., 2021; Trivedi et al., 2021).

A MODE 4 FRAMEWORK (4F BIOECONOMY MODEL) FOR MICROBIOME-BASED SUSTAINABLE FRUIT PRODUCTION IN INDIA

A four-pillar, systems-oriented framework 4F- Bioeconomy model (Fodder- Fuel– Fruits – Forests) designed for Indian fruit systems, a biomass centred Green solution to remediate degraded lands, integrating existing concepts of microbiome-driven cropping to enhance sustainable fruit production in India (Nadarajah & Rahman, 2023; Srivastava et al., 2021).

Microbiome Engineering Elements Relevant to Indian Fruit Systems

Figure 1: Conceptual Four-Pillar Framework for Microbiome-Based Fruit Systems in India

Mode 4 Pillar	Features	Example	Citations
1. Diagnosis & mapping	Identifying native microbiomes in major fruit crops and regions for suppression, abiotic, stress management and nutrient acquisition.	Metagenomic surveys of mango, citrus rhizosphere	(Nadarajah & Rahman, 2023; Srivastava et al., 2021; Suman et al., 2022; Singh et al., 2020; Trivedi et al., 2021)
2. Design & integrated post-microbial co-optimization	Develop stable combinations of PGPR and ISFM packages exclusively for a specific fruit crop.	Optimizing usage of Biofertilizer, organic manure, vermicompost and minimal mineral fertilization.	(Mahmud et al., 2021; Srivastava et al., 2021; Singh et al., 2020; Qiu et al., 2019; O'Callaghan et al., 2022; Batista & Singh, 2021)
3. Host–microbiome co-optimization	Breeding cultivars that favour the growth of beneficial microbiomes	Use of M genes, CRISPR-based host traits	(Kumar & Dubey, 2020; Kaul et al., 2021; Thakur et al., 2023; Afridi et al., 2022; Bano et al., 2021; Trivedi et al., 2021)
4. Scale & government support	Emphasis on large scale implementation instead of fragmented plots. Availing government incentives and subsidies	Standards for inoculants; training for growers	(Mahmud et al., 2021; Srivastava et al., 2021; O'Callaghan et al., 2022; Batista & Singh, 2021)

Pillar 1: Diagnosis and Mapping

Using metagenomics approach the current soil profile is understood and crop specific characterization of fruit crop microbiome, its diversity, functional potential and response to management is assessed (Nadarajah & Rahman, 2023; Srivastava et al., 2021; Suman et al., 2022; Singh et al., 2020). Actions include:

- Key Indian fruit crop (mango, citrus, banana, pomegranate, guava, grapes) specific mapping of rhizosphere and endosphere microbiomes across agro-climatic zones.
- Analysing how conventional, organic and ISFM systems regulates the link between microbiome profile and fruit yield, fruit quality and soil health (Srivastava et al., 2021; Suman et al., 2022).
- Determining indicator taxa and key functional genes responsible for disease suppression and stress resilience.

Pillar 2: Design and Integration

Through the combined use of microbial consortia, mineral fertilizers and organic inputs, ISFM facilitates microbial engineering in fruit orchards (Srivastava et al., 2021). Research evidence shows that better fulfilment of nutrient demand and improvement of soil health than generic formulations can be achieved through rhizospherespecific consortia, developed by scaling up cropspecific microbiomes (Srivastava et al., 2021; Singh et al., 2020; Qiu et al., 2019).

For Indian fruit crops, this pillar would involve:

- Designing fruit crop–specific consortia of N-fixing, P-solubilizing, mycorrhizal, and biocontrol microbes which are adapted to Indian soils and climates.
- Incorporating these tailored consortia into integrated packages with composting, green manuring, mulching and reduced synthetic inputs (Srivastava et al., 2021).

- Long-term impacts on yield stability, fruit nutritional quality, soil carbon sequestration, and greenhouse gas emission are evaluated (Nadarajah & Rahman, 2023; Srivastava et al., 2021; Suman et al., 2022; Afridi et al., 2022).

Pillar 3: Host–Microbiome Co-Optimization

More consistent field performance can be achieved by Co optimizing or Co designing plant genotypes and microbiomes (Kumar & Dubey, 2020; Kaul et al., 2021; Trivedi et al., 2021).

For perennial fruit crops, key steps include:

- Selecting a varied range of Indian and exotic plant varieties to understand their traits which triggers the growth of specific microbial consortia associated with improved crop performance under various abiotic and biotic stresses (Kaul et al., 2021; Thakur et al., 2023; Afridi et al., 2022).
- Developing fruit varieties using various gene editing tools which can encourage the growth of host beneficial consortia (e.g., improved exudate profiles) (Kumar & Dubey, 2020; Kaul et al., 2021; Thakur et al., 2023; Bano et al., 2021).
- Manipulating the microbiome at the early seed and nursery stage-specifically coating seeds and inoculating young plants-ensures the early colonisation of beneficial microbial consortia (Kumar & Dubey, 2020; Afridi et al., 2022; Qiu et al., 2019).

Pillar 4: Scaling, Governance, and Farmer Adoption

Global studies show that lack of rigorous quality standards, customized application guidance and active engagement from the farmers using them, microbial products often fail to meet the expectations (Mahmud et al., 2021; O'Callaghan et al., 2022; Batista & Singh, 2021). For Indian fruit cultivation systems, this pillar involves the following:

- For rigorous scrutiny on strain purity, identity, viability and proven field results, strict guidelines and legal structures are necessary (O'Callaghan et al., 2022; Batista & Singh, 2021).
- To test the effectiveness of microbial consortia and management practices, it is essential to conduct extensive field trials in real- world fluctuating environmental and ecological conditions in India (Mahmud et al., 2021; Srivastava et al., 2021; O'Callaghan et al., 2022; Batista & Singh, 2021).
- For promoting microbiome tools by smallholders and commercial orchards, extension programs, participatory research, and market incentives are necessary to encourage organic and climate-smart horticulture (Srivastava et al., 2021; Batista & Singh, 2021).

CHALLENGES, RISKS, AND KNOWLEDGE GAPS

Despite rapid success and progress, there are several constraints that restricts widespread application of microbiome engineering in fruit crops:

India shows variations across different soil types, climatic zones, water availability topography and management practices, this is the primary challenge in context-dependent performance of microbial inoculants (Nadarajah & Rahman, 2023; Mahmud et al., 2021; O'Callaghan et al., 2022; Batista & Singh, 2021). Furthermore, the long-lived trees create a

complex decadal interaction with the local microbiome, and such long-term data remains insufficient in the Indian horticultural landscape (Kumar et al., 2021; Srivastava & Malhotra, 2022). Current research also suffers from a taxonomic and crop bias, mostly focussing on microbiome-engineering research on cereals (e.g., rice) and annuals rather than the specific needs of perennial fruit systems (Srivastava et al., 2021; Singh et al., 2020; Afridi et al., 2022). Additionally, there are significant biosafety and ecological concerns which arises due to use of genetically engineered microbes that can cause non-targeted modifications in the ecosystem (Nadarajah & Rahman, 2023; Kaul et al., 2021; Thakur et al., 2023; Trivedi et al., 2021; Batista & Singh, 2021). Finally, the successful implementation of multi-omics, bioinformatics, and high-throughput microbiology require investments and cross-disciplinary training that are at nascent stage in many Indian academic and research institutions (Kaul et al., 2021; Thakur et al., 2023; Trivedi et al., 2021).

CONCLUSION

Microbiome engineering offers a strong, science-based pathway to increase productivity, environmental sustainability, and fruit quality in Indian horticulture. By emphasizing on the health and synergy of the plant's microbial ecosystem, biocontrol, in situ manipulation and host – microbiome optimization, farmers can move away from industrial chemicals and toward a more sustainable, biologically driven farming model. A Mode 4 framework focusing on diagnosis and map, design and integrate, co-optimize hosts and microbiomes and scale through supportive policies and market can surely offers a systematic roadmap for advancing fruit cultivation in India.

REFERENCES

1. Adedayo, A. A., et al. (2022). *Harnessing rhizosphere microbes: the synergistic roles of PGPR and AMF in sustainable tomato production under stress*. *Frontiers in Microbiology*, 13.
2. Afridi, M. S., Javed, M. A., Ali, S., de Medeiros, F. H. V., Ali, B., Salam, A., ... Santoyo, G. (2022). *New opportunities in plant microbiome engineering for increasing agricultural sustainability under stressful conditions*. *Frontiers in Plant Science*, 13, Article 899464. <https://doi.org/10.3389/fpls.2022.899464>
3. Alam, G. M. M., Khatun, M. N., Sarker, M. N. I., Joshi, N. P., & Bhandari, H. (2023). *Promoting agri-food systems resilience through ICT in developing countries amid COVID-19*. *Frontiers in Sustainable Food Systems*, 6. <https://doi.org/10.3389/fsufs.2022.972667>
4. Bano, S., Wu, X., & Zhang, X. (2021). *Towards sustainable agriculture: Rhizosphere microbiome engineering*. *Applied Microbiology and Biotechnology*, 105(17), 6365–6381. <https://doi.org/10.1007/s00253-021-11555-w>
5. Batista, B. D., & Singh, B. K. (2021). *Realities and hopes in the application of microbial tools in agriculture*. *Microbial Biotechnology*, 14(4), 1258–1270. <https://doi.org/10.1111/1751-7915.13866>
6. Bhardwaj, R. L., Sarolia, D. K., Mukherjee, S., & Yadav, P. K. (2010). *Role of bio-fertilizers in fruit crops for sustainable agriculture*. *International Journal of Fruit Science*, 10(2).
7. Dutta, P., & Kundu, S. (2012). *Effect of bio-fertilizers on fruit quality and leaf mineral content of mango cv. Himsagar*. *Journal of Crop and Weed*, 8(1), 115-118.

8. Kaul, S., Choudhary, M., Gupta, S., & Dhar, M. K. (2021). Engineering host microbiome for crop improvement and sustainable agriculture. *Frontiers in Microbiology*, 12, Article 635917. <https://doi.org/10.3389/fmicb.2021.635917>
9. Kumar, A., & Dubey, A. (2020). Rhizosphere microbiome: Engineering bacterial competitiveness for enhancing crop production. *Journal of Advanced Research*, 24, 337–352. <https://doi.org/10.1016/j.jare.2020.04.014>
10. Mahmud, K., Missaoui, A., Lee, K., Ghimire, B., Presley, H., & Makaju, S. (2021). Rhizosphere microbiome manipulation for sustainable crop production. *Current Plant Biology*, 26, 100198.
11. Mon, Y. Y., Bidabadi, S. S., Oo, K. S., & Zheng, S. J. (2021). The antagonistic mechanism of rhizosphere microbes and endophytes on the interaction between banana and *Fusarium oxysporum* f. sp. *cubense*. *Physiological and Molecular Plant Pathology*, 116, 101733. <https://doi.org/10.1016/j.pmpp.2021.101733>
12. Nadarajah, K., & Abdul Rahman, N. S. N. (2023). The microbial connection to sustainable agriculture. *Plants*, 12(11), 2061. <https://doi.org/10.3390/plants12122307>
13. O'Callaghan, M., Ballard, R. A., & Wright, D. (2022). Soil microbial inoculants for sustainable agriculture: Limitations and opportunities. *Soil Use and Management*, 38(2), 1344–1364. <https://doi.org/10.1111/sum.12811>
14. Qiu, Z., Egidi, E., Liu, H., Kaur, S., & Singh, B. K. (2019). New frontiers in agriculture productivity: Optimised microbial inoculants and in situ microbiome engineering. *Biotechnology Advances*, 37(6), 107371. <https://doi.org/10.1016/j.biotechadv.2019.03.010>
15. Sharma, A., et al. (2023). Systematic analyses with genomic and metabolomic insights reveal a new species, *Ophiocordyceps indica* sp. nov. from treeline area of Indian Western Himalayan region. *Frontiers in Microbiology*, 14. <https://doi.org/10.3389/fmicb.2023.1188649>
16. Singh, B. K., Trivedi, P., Egidi, E., Macdonald, C. A., & Delgado-Baquerizo, M. (2020). Crop microbiome and sustainable agriculture. *Nature Reviews Microbiology*, 18(11), 601–602. <https://doi.org/10.1038/s41579-020-00446-y>
17. Srivastava, A. K., Wu, Q., Mousavi, S. M., & Hota, D. (2021). Integrated soil fertility management in fruit crops: An overview. *International Journal of Fruit Science*, 21(1), 1–32. <https://doi.org/10.1080/15538362.2021.1895034>
18. Suman, J., Rakshit, A., Ogireddy, S. D., Singh, S., Gupta, C., & Chandrakala, J. (2022). Microbiome as a key player in sustainable agriculture and human health. *Frontiers in Soil Science*, 2, Article 821589. <https://doi.org/10.3389/fsoil.2022.821589>
19. Thakur, N., Nigam, M., Mann, N., Gupta, S., Hussain, C. M., Shukla, S. K., ... Khan, S. A. (2023). Host-mediated gene engineering and microbiome-based technology optimization for sustainable agriculture and environment. *Functional & Integrative Genomics*, 23(1), 24. <https://doi.org/10.1007/s10142-023-00982-9>
20. Trivedi, P., Mattupalli, C., Eversole, K., & Leach, J. E. (2021). Enabling sustainable agriculture through understanding and enhancement of microbiomes. *New Phytologist*, 230(6), 2129–2147. <https://doi.org/10.1111/nph.17319>