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Harnessing the Functional Plant Microbiomes for Next Generation Plant Health Management Strategies

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CONVENER : Dr. M.S. Saharan, Head, Division of Plant Pathology, ICAR-Indian Agricultural Research Institute, New Delhi

CO-CONVENER : Dr. Aundy Kumar, Professor, Division of Plant Pathology, ICAR-Indian Agricultural Research Institute, New Delhi

REVIEWERS : Dr. T.K. Adhya, Former Director, ICAR-Central Rice Research Institute, Bhubaneswar

Dr. A.K. Saxena, Former Director, ICAR-National Bureau of Agriculturally Important Microorganisms, New Delhi

EDITORS : Dr. R.K. Jain

Dr. R.K. Pal

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NASC, Dev Prakash Shastry Marg, New Delhi - 110 012, India
Tel: (011) 25846051
Email: naas-mail@naas.org.in; Website: www.naas.org.in

Preface

Plant- and soil- associated microbiomes form the biological foundation for next-generation plant health management by regulating nutrient acquisition, modulating plant immunity, enhancing tolerance to abiotic stresses, suppressing pathogens and pests, and contributing to agro-ecosystem stability. Despite considerable scientific progress, the systematic application of functional plant microbiomes in plant health management is yet to be fully integrated into Indian agriculture.

To evaluate the current state of research, identify knowledge gaps, and outline strategic and policy directions for advancing microbiome-based approaches, the Academy organized a brainstorming session on *“Harnessing the Functional Plant Microbiomes for Next Generation Plant Health Management Strategies”* to discuss scientific validation, regulatory considerations, product development, and pathways for large-scale adoption.

This policy paper presents a framework for integrating functional microbiomes approaches into mainstream plant health management. Key recommendations include crop- and region-specific interventions, development of functionally characterized microbial consortia, standardized validation and biosafety protocols, regulatory streamlining for microbiome-based products, structured monitoring systems, and strengthened public–private collaboration. Emphasis has been laid on aligning microbiome-based strategies with national plant protection priorities and long-term sustainability goals.

On behalf of the Academy, I complement the Convener (Dr. M.S. Saharan), Co-convener (Dr. Aundy Kumar) and other eminent experts for their valuable inputs in developing the policy paper. My thanks are also due to the Reviewers (Dr. T.K. Adhya & Dr. A.K. Saxena) and Editors (Dr. R.K. Jain & Dr. R.K. Pal) for their valuable observations and editorial support. I am hopeful that this document will be useful to the policy makers and other stakeholders.

May 2026
New Delhi

(M.L. Jat)
President, NAAS

Harnessing the Functional Plant Microbiomes for Next Generation Plant Health Management Strategies

1. INTRODUCTION

Plant disease and pest management is entering a transformative phase that moves beyond reliance on chemical pesticides and single-gene resistance. Emerging strategies such as precision surveillance, rapid molecular diagnostics, resistant cultivar development, RNA interference & Gene editing based protection, biological control agents, and integrated pest management aim to enhance intervention effectiveness, reduce chemical dependence, & maintain ecological balance. Within this shift, plant-associated microbiomes are increasingly recognized as a foundational biological component capable of reinforcing plant defence, moderating pest & pathogen pressure, and stabilizing plant health under diverse field conditions.

Plants interact closely with diverse communities of beneficial microorganisms in the rhizosphere, endosphere, and phyllosphere that support nutrient acquisition, stress tolerance, and protection against pests and diseases (Berendsen *et al*., 2012). Plant genotype partly determines microbiome composition, making microbiome recruitment a heritable trait that can be considered in crop breeding to improve plant health and productivity (Escudero-Martinez and Bulgarelli, 2023). Advances in microbiome research, particularly high-throughput sequencing, have enabled detailed characterization of plant-associated microbial communities and their functional interactions with plants and soils (Berg *et al*., 2020). Moreover, the development of functionally validated microbial consortia, beyond single-strain bio-inputs, has strengthened microbiome-informed plant health strategies. Plant microbiome genes (M-genes), which regulate the assembly of plant-associated microbial communities, provide promising targets for engineering microbiomes that enhance plant growth and stress resilience (Cernava, 2024).

In India, interest in microbiome-based approaches has grown in view of soil degradation, climate variability, and the declining effectiveness of chemical-intensive farming systems (NAAS, 2018; 2025). Research institutions are documenting microbial diversity across crops and agro-ecological regions and identifying functional traits linked to disease suppression, nutrient cycling, & tolerance to abiotic stresses (Kumar *et al*., 2025). Microbial bio-inputs are increasingly integrated into soil health management, organic & natural farming, and broader crop management programmes. As summarized in Fig. 1, Indian agri-biological industry has expanded significantly in recent years, reflecting growing demand for sustainable crop protection solutions, increasing adoption of bio-inputs by farmers, and supportive government policies promoting eco-friendly agriculture. The compound annual growth rate (CAGR) of 14.13% is projected for the period 2023-2032. Despite this growth, adoption and consistent field performance remain limited due to fragmented research, insufficient multi-location validation, and the

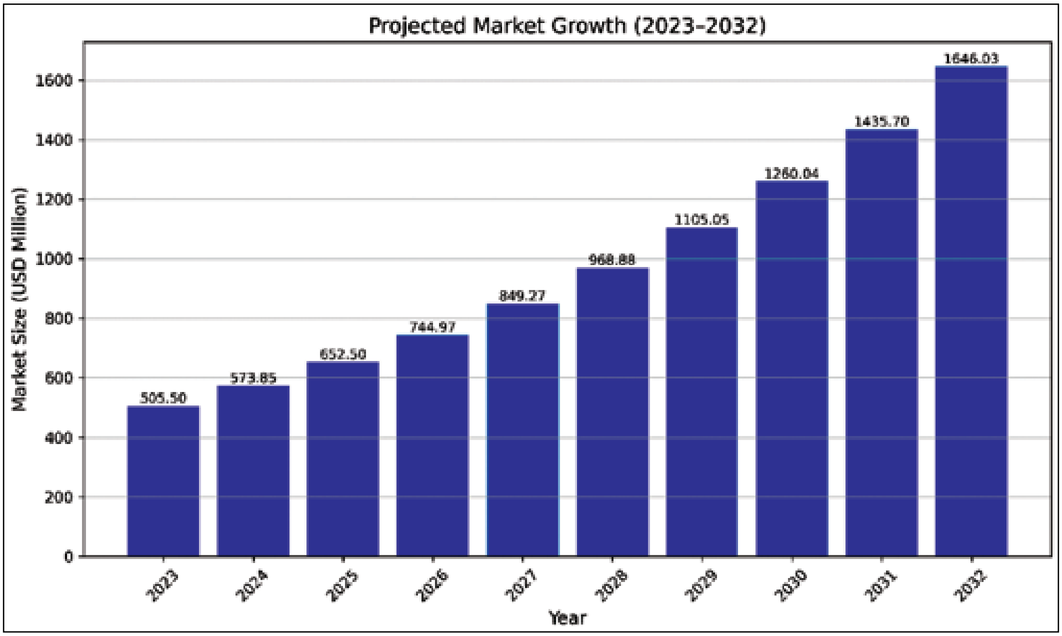

Figure 1. Indian Agri-biologicals Market Size and Growth Forecast (2023–2032) with CAGR Analysis (Data Courtesy: https://www.fortunebusinessinsights.com/india-agricultural-biologicals-market-108560; Accessed on February 20, 2026)

absence of harmonized regulatory standards. India's rich microbial diversity provides opportunities to design crop- and region-specific microbiome interventions that reduce chemical inputs, enhance resilience, and strengthen plant health management systems.

Advances in systems biology, data analytics, and long-term field experimentation now support the development of functionally validated microbial consortia that enhance disease suppression, improve nutrient-use efficiency, and stabilize productivity under climatic stress (Trivedi *et al.*, 2020). International programmes on agricultural microbiomes integrate research with plant breeding, agronomy, and crop protection, emphasizing long-term field trials, locally adapted microbial consortia, regulatory frameworks, quality assurance, and public–private collaboration to ensure safe & effective deployment (Trivedi *et al.*, 2020). These experiences offer valuable lessons for strengthening plant health management in India. Integrating functional plant microbiomes into next-generation strategies reinforces natural defence mechanisms, enhances biological regulation of pests & diseases, and supports resilient, resource-efficient production systems aligned with long-term food security & environmental sustainability.

2. PROBLEM STATEMENT

Despite advances in microbiome science and growing evidence of their role in nutrient cycling, stress tolerance, and disease suppression (van der Heijden *et al.*, 2008), functional plant microbiomes are not yet systematically embedded in plant health management frameworks in India. Scientific progress has outpaced institutional integration, regulatory preparedness, and field-level validation.

A central constraint is the limited understanding of microbiome performance across India's diverse agro-ecological regions and management systems. Research initiatives are often crop- or location-specific, with insufficient long-term and multi-location validation. As illustrated in Fig. 2, effective microbiome-based plant health enhancement requires a structured continuum from microbial discovery and functional characterization to validation, formulation, and field deployment. Breaks along this continuum have limited translation into scalable applications. Consequently, microbial inoculants and bio-inputs frequently show inconsistent performance under farmers' conditions, reducing confidence and adoption. The absence of harmonized standards for efficacy testing, strain characterization, formulation quality, and shelf-life validation further constrain reliability & scale (OECD, 2019).

Institutional fragmentation further constrains the translation of microbiome science into practical plant health solutions. Research, regulation, industry development, and extension services operate without a unified framework, limiting the development of region-specific applications. Regulatory ambiguity creates uncertainty for product

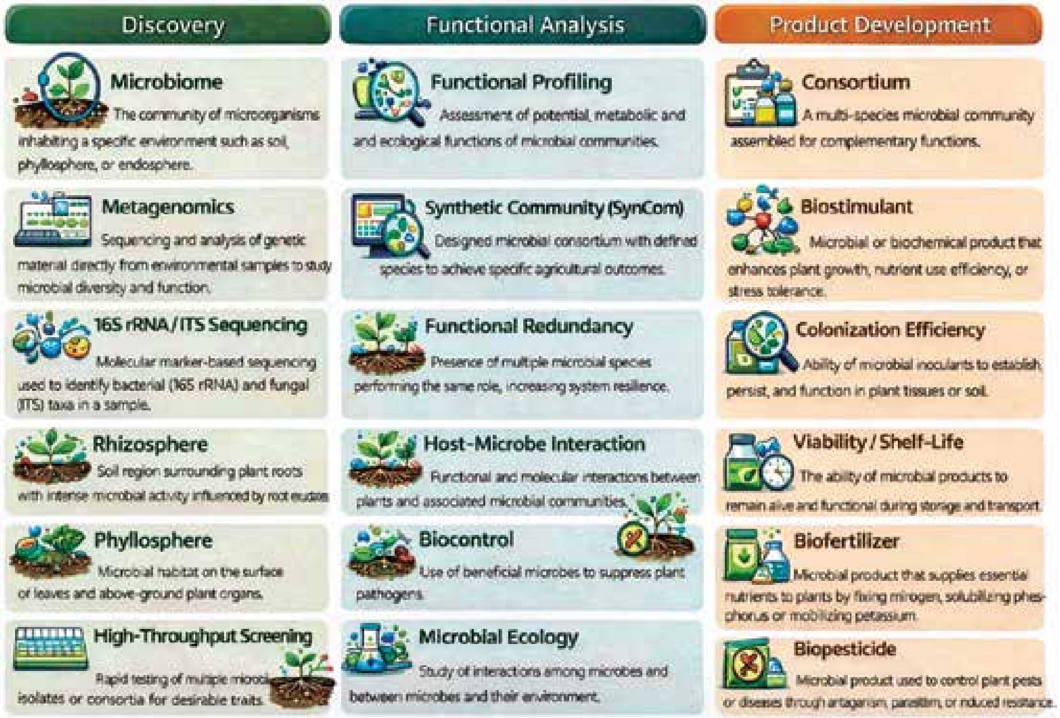

Figure 2. Core Concepts and Work Flow in Microbiome Discovery, Analysis and Application

development and commercialization, while the lack of validated deployment models slows integration into crop management systems. As a result, chemical-intensive practices continue to dominate in the absence of reliable biological alternatives. These systemic gaps prevent effective utilization of India's microbial diversity and scientific capacity. Although advances in plant microbiome research offer opportunities to develop improved microbial applications for sustainable crop production, challenges remain in achieving consistent field performance (Compant *et al*., 2025). A coordinated, policy-driven framework is therefore needed to establish microbiome integration as a core component of next-generation plant health systems.

3. POLICY OBJECTIVES

In order to position functional plant and soil microbiomes as integral components of next-generation plant health management, there is a need to embed microbiome-based strategies within plant health system in a scientifically rigorous, regionally adapted, farmer-oriented, and environmentally responsible manner.

Initially, priority should be given to establish a coordinated national framework for functional microbiome research, multi-location field validation, and data sharing. Focus will be laid on major crops, diverse agro-ecological regions, and key stress scenarios where microbiome interventions can enhance disease management, nutrient-use efficiency, climate resilience, and postharvest protection. The framework will include clear regulatory pathways, harmonized quality standards, and standardized efficacy protocols to ensure the safety, reliability, and scalability of microbial products. Strengthening institutional capacity across research organizations, diagnostic laboratories, extension systems, and industry will be essential for effective implementation. In parallel, standardized protocols for sampling, data documentation, microbial and environmental DNA isolation, sequencing, and analysis will be developed to ensure consistency and comparability of microbiome datasets nationwide.

Subsequently, microbiome-based strategies will be systematically integrated into national programmes on plant protection, soil health, climate resilience, and sustainable agriculture. These efforts will focus on reducing dependence on chemical fertilizers and pesticides, while maintaining productivity, improving yield stability under biotic & abiotic stresses, and promoting agronomic practices that enhance beneficial plant–microbe interactions. The policy will support mission-oriented research, encourage the responsible utilization of native microbial resources, and promote structured public–private partnerships to facilitate product development, validation, and large-scale field deployment.

The expected outcomes include improved soil biological function, enhanced nutrient-use efficiency, reduced chemical input intensity, and wider adoption of validated microbiome-based practices, particularly in climate-vulnerable and resource-constrained regions. Strengthened disease management, improved stress tolerance, and reduced postharvest losses are anticipated to contribute to yield stability and greater income security for farmers. These objectives align with national development priorities and commitments under the Sustainable Development Goals (SDGs), reinforcing resilience and long-term sustainability in agricultural production systems.

4. SCIENTIFIC AND TECHNICAL EVIDENCE BASE FOR MICROBIOME ASSISTED PLANT HEALTH ENHANCEMENT

Plant health is strongly influenced by the structure and function of microbial communities associated with crops. Functional microbiomes in the rhizosphere, endosphere, and phyllosphere contribute to nutrient acquisition, disease suppression, and tolerance to abiotic stress (Vandenkoornhuyse *et al.*, 2015). Advances in molecular tools and high-throughput sequencing have enabled detailed characterization of microbial communities and their functional attributes, strengthening the scientific basis for microbiome-informed plant health management. A critical development in this field is the transition from single-strain bio-inputs to microbiome-based product development that employs synergistically active microbial consortia. Such consortia provide broader functional capacity, greater ecological stability, and improved adaptability across variable field conditions.

Beneficial microorganisms regulate plant–pathogen interactions through competition, antibiosis, parasitism, and induction of systemic resistance, thereby lowering disease incidence and severity. They also improve nutrient-use efficiency—particularly for nitrogen and phosphorus—strengthening plant vigor and resilience (van der Heijden *et al*., 2008). Certain microbial communities enhance tolerance to drought, heat, and salinity, supporting crop performance under climatic stress. Collectively, this body of evidence establishes a strong scientific basis for integrating functional plant microbiomes into structured plant health enhancement strategies.

Evidence from Indian cropping systems shows that microbiome-based interventions can reduce disease pressure and improve crop performance when aligned with local agro-ecological conditions (Kumar, 2025). International experience further demonstrates that durable plant health benefits depend on multi-location field validation, quality-assured formulations, and integration with sound agronomic practices (Bashan *et al.*, 2014. The selection and deployment of native, locally adapted microbial strains remain central to consistent disease management outcomes. At both national and international levels, microbiome-based multi-species agricultural products—including microbial consortia and synthetic community technologies—are being developed to provide stable, broad-spectrum growth promotion (Table 1). In the Indian context, microbiome-based bioproducts for crop protection are still largely unavailable, primarily due to the absence of a clear and well-defined regulatory and policy framework. However, numerous single-strain–based products (970) approved by the Central Insecticides Board and Registration Committee (CIBRC) are available in India (Saxena *et al*., 2020; https://www.ppqs.gov.in/en/divisions/cib-rc/bio-pesticide-registrant). Field evidence indicates that sustained outcomes require crop- and region-specific design, appropriate delivery methods, and informed farmer adoption. These findings highlight the importance of structured validation systems, robust quality standards, and effective extension mechanisms to translate microbiome science into reliable field applications. Collectively, the available evidence supports the integration of functional plant microbiomes into plant health management systems. Documented

Table 1. Microbiome-based Multi-species Agricultural Products: Consortia and Synthetic Community Technologies

Product Name	*Manufacturer/ Government Agency	Microbiome Composition/ Technology	Primary Function
		India	
PUSA Biophos	ICAR-IARI	Phosphate-solubilizing bacteria (PSB)	Biofertilizer
PUSA Biopotash		Potash-mobilizing bacteria (KMB)	Biofertilizer
PUSA Bio Zinc		Zinc-solubilizing microbes	Biofertilizer
PUSA Sampoorn		Multi-strain microbial consortium	Biofertilizer
PUSA Decomposer		Multi-strain microbial consortium	Decomposer
NRRI-Endo NPK	ICAR-CRRI	Endophytic microbial consortium	Biofertilizer
Biofertilizer Consortium (Rice–Vegetable System)		Multi-functional microbiome	Biofertilizer
Bio NPK Liquid Consortium	ICAR-NBAIM	N-fixers + PSB + KMB	Biofertilizer
Bioenhancer	ICAR-CISH	Microbial + organic consortia	Biostimulant
		USA	
iNvigorate®	AMVAC / Agrinos	Complex consortium of 22 species of aerobic and anaerobic bacteria	Soil health restoration & multi-nutrient (N, P, K) mobilization
BiOWiSH® Crop Liquid	Biowish Technologies	Multi-species consortium utilizing HoloGene 3™ technology to shift native soil microbiomes	Enhances nutrient uptake and improves fertilizer efficiency
Mammoth P®	Growcentia	Four-species functional consortium (*Comamonas*, *Pseudomonas*, *Enterobacter*, *Citrobacter*)	Specifically engineered to unlock "locked" phosphorus in soil
Rhizolizer® Duo	Locus AG	High-density endophytic consortium of *Trichoderma* and *Bacillus* strains	Colonizes the internal plant microbiome for carbon sequestration and yield
		Canada	
Synergiro®	Concentric Agriculture	Co-fermented "living" consortium of microbes and their active metabolites	Mimics a high-functioning compost microbiome to boost plant vigor

Contd...

Product Name	*Manufacturer/ Government Agency	Microbiome Composition/ Technology	Primary Function
		Brazil	
BiomaPhos®	Embrapa / Bioma	Bacterial consortium of *Bacillus subtilis* and *B. megaterium*	Brazil's first registered consortium for phosphorus absorption in grain crops
PASTOMAX®	Embrapa / Biotrop	Triple-action consortium (*Azospirillum*, *Pseudomonas*, and others)	Specifically designed to regenerate the microbiome of degraded pasture lands

*ICAR-IARI: ICAR–Indian Agricultural Research Institute, New Delhi; ICAR-CRRI: ICAR-Central Rice Research Institute, Cuttack; ICAR-NBAIM: ICAR–National Bureau of Agriculturally Important Microorganisms, Mau; ICAR-CISH: ICAR–Central Institute of Subtropical Horticulture, Lucknow

benefits include reduced disease incidence, improved plant vigor, enhanced stress tolerance, and decreased reliance on chemical pesticides. With appropriate validation and regulatory oversight, microbiome-based approaches can strengthen plant health and contribute to more resilient cropping systems in India

5. POLICY OPTIONS AND ALTERNATIVES

Strengthening plant health under increasing climate variability and rising pest and disease pressures requires a clear strategic direction. The prevailing crop protection model, based largely on host resistance breeding and the use of chemical fertilizers and pesticides, has supported productivity gains but is increasingly constrained by soil biological degradation, pest resistance, and unstable performance under climatic stress (FAO, ITPS, GSBI, SCBD and EC, 2020). Fragmented microbiome research and regulatory systems designed primarily for conventional inputs further limit progress.

A gradual integration approach, based on pilot initiatives within existing frameworks, provides a cautious transition but remains limited in impact due to weak coordination, absence of standardized quality protocols, and insufficient multi-location validation. Inconsistent standards and inadequate field testing have contributed to variable performance of microbial products, reducing confidence among farmers and industry.

A coordinated approach integrating functional plant microbiomes into plant health systems provides a more consistent pathway. Plant-associated microbial communities contribute to nutrient acquisition, activation of plant defence mechanisms, and suppression of pathogens (Busby *et al.*, 2017). International guidance emphasizes regulatory clarity, quality assurance, and monitoring systems to ensure reliability and public confidence (OECD, 2019). This approach requires stronger institutional coordination and investment but supports improved disease management, enhanced soil biological function, reduced chemical dependence, and greater yield stability under climate stress.

Implementation requires a structured framework linking regulation, research, and field application. Regulatory systems should establish clear procedures for evaluation, approval, quality assurance, and post-release monitoring of microbiome-based products. Standards should define strain identity, functional traits, formulation stability, shelf life, and field performance across agro-climatic conditions, supported by environmental safety assessment and transparent certification systems (Schmidt *et al.*, 2019). Existing provisions for biofertilizers and biopesticides provide a base but do not adequately address functionally characterized microbial consortia (Berg *et al.*, 2020).

Research and validation should be strengthened through regional centres supported by multi-location and long-term field trials to generate evidence under farmer-managed conditions. Functional microbiome research should be aligned with plant health programmes, crop improvement efforts, and advisory systems. Financial support should prioritize long-term experimentation, validated microbial consortia, and demonstration programmes in climate-vulnerable regions. Public private partnerships and competitive funding mechanisms can support product development, quality production, and scaling.

Implementation should proceed in phases, beginning with characterization of soil and plant microbiomes in priority crops and regions to identify functional traits related to disease suppression, nutrient cycling, and stress tolerance, followed by field validation and farmer-led demonstrations. Capacity development is required across researchers, extension personnel, and farmers, supported by strengthened laboratory infrastructure, data systems, and long-term field platforms. Inclusion of microbiome science in academic and professional training will support continuity.

A National Coordination Committee on Functional Plant Microbiomes may be constituted to align research, regulation, and implementation. Regional Microbiome Hubs should undertake crop- & region-specific research, multi-location validation, and field demonstrations, supported by a centralized data platform documenting microbial strains, functional traits, &field performance. Public–private collaboration will support translation into field-ready technologies. Certified microbiome-based products should be distributed through regulated systems.

Financial support is required across stages of implementation, including research, validation, regulatory strengthening, extension, and deployment. Initial investments should support pilot programmes, functional characterization, and capacity building. Medium-term support should focus on regional centres, validation trials, and integration into national programmes. Long-term support should cover large-scale deployment, formulation development, and environmental monitoring. Resources may be mobilized through Ministry of Agriculture and Farmers' Welfare and Indian Council of Agricultural Research along with alignment to initiatives such as the National Mission for Sustainable Agriculture, Soil Health programmes, Natural Farming & Organic Agriculture initiatives, the National Plant Health Mission, and Rashtriya Krishi Vikas Yojana.

Monitoring and evaluation systems should assess adoption across regions, reduction in chemical input use, improvement in disease suppression and soil biological activity, enhancement of nutrient-use efficiency, and stability of crop productivity (Trivedi *et al*., 2020). Data generated through regional centres and long-term field platforms should be periodically reviewed for any policy adjustment. Farmers' feedback should be incorporated to improve formulations and advisory services (Berg *et al*., 2020).

Safeguards are necessary to address ecological, agronomic, and social considerations. Introduction of microbial strains without adequate assessment may affect native microbial communities and ecosystem balance (Berg *et al*., 2020). Priority should be given to native or locally adapted strains supported by multi-location validation and long-term monitoring. Regulatory systems should enforce standards for strain identification, functional characterization, formulation quality, and biosafety compliance. Equitable access requires inclusion of smallholder and climate-vulnerable farmers, supported by technical guidance in local languages and participatory field evaluation (Mendes *et al*., 2011). These measures support responsible and balanced deployment of microbiome-based plant health strategies (Busby *et al*., 2017).

6. RECOMMENDATIONS

In order to build climate-resilient sustainable agriculture, improve farmers income, conserve natural resources, and reduce chemicals input dependence, microbiome-based strategies need to be integrated with National Plant Health Mission (NPHM), a recent initiative of ICAR for strengthening crop protection at national level. Crop-specific core or hub microbes, identified through comparative microbiome profiling, may facilitate the development of synthetic microbial communities (SynComs) to pre-empt pathogens and enhance plant health. Microbiome (M) gene -mediated resistance may further complement R-gene–based resistance where available. Distribution of microbiome-fortified seeds and planting material may ensure healthy, and disease-free crop establishment.

A coordinated microbiome-based digital system may be developed using field sensors, drones, and digital platforms to integrate soil and foliar health, microbiome/pathobiome repository & database, and disease/pathogen data for real time monitoring and early warning. Sensor-based diagnostics and drone surveillance may support rapid detection of disease hotspots and guide need-based, location-specific microbiome interventions. The following recommendations outline the plant health centric approach to harness plant microbiomes:

Initial Phase (1-3 years)

1. **Prioritize Research and Multi-location Validation for Disease Management:** Research institutions, plant protection services, soil health programmes, industry, and extension systems should operate within a unified framework that promotes crop- and region-specific microbiome research. Support regional hubs for focused research on rhizosphere, phyllosphere, and endosphere microbiomes linked to pathogen suppression and stress tolerance. Conduct multi-location field trials across priority crops and agro-ecological zones to validate efficacy under diverse disease pressures and climatic conditions.

2. **Build Diagnostic, Extension, and Institutional Capacity for Plant Health:** Strengthen laboratory infrastructure for microbial characterization, pathogen diagnostics, and bio-safety testing. Train extension personnel and farmer groups in microbiome-based plant health practices, including correct application, integration with existing crop protection strategies, and monitoring of disease outcomes.

3. **Mobilize Sustained Investment for Disease-resilient Systems:** Align funding through central and state schemes with priority given to biological disease management, microbiome stabilization, and long-term soil health restoration, supported by phased public–private investment. A shared financing model—public investment for research and validation, joint support for extension, and industry-led commercialization under regulatory oversight—will facilitate responsible scaling and long-term sustainability.

4. **Strengthen National Microbiome Repositories for Plant Health Applications:** Strengthen and integrate existing microbiome resources, including National Bureau of Agriculturally Important Microorganisms (NBAIM), Mau; National Centre for Cell science (NCCS), Pune and Institute of Microbial Technology (IMTECH), Chandigarh. A coordinated approach under ICAR, DBT and CSIR can link these facilities toimprove characterization & standardization of functionally important plant-associated microbial communities, support quality assurance, enable rapid deployment during emerging disease outbreaks, and facilitate research to enhance plant health & resilience, alongside existing pure culture collections.

5. **Integrate Microbiome-based Approaches with Integrated Pest and Disease Management:** Position functional plant microbiomes as a core component of integrated pest and disease management systems, combining biological suppression, host resistance, cultural practices, and need-based chemical use to ensure durable plant health and long-term sustainability.

Medium Phase (>3-5 years)

6. **Encourage Public–Private Partnerships for Plant Health Innovation:** Facilitate collaboration among research institutions, state agencies, and industry for development, quality production, validation, and dissemination of plant health–oriented microbial products.

7. **Implement Plant Health–focused Monitoring and Evaluation:** Establish measurable indicators such as reduction in disease incidence and severity, improved crop vigor, enhanced nutrient-use efficiency, reduced chemical pesticide load, and yield stability. Establish and link AI-ML based monitoring systems with regular review and corrective action mechanisms.

Long Phase (>5 years)

8. **Strengthen Regulatory Frameworks for Plant Health Microbial Products:** A structured regulatory framework is essential to assess the performance and impact

of microbiome-based plant health interventions. Develop clear regulatory pathways and quality standards for microbial consortia designed for disease suppression, induced resistance, and microbiome stabilization. Regulatory provisions should move beyond single-strain approvals to accommodate ecology-driven, multi-strain formulations validated for plant health outcomes.

9. **Promote Inclusive, and Region-specific Deployment for Vulnerable Farming Systems:** Target small and marginal farmers, climate-stressed regions, and areas with chronic soil-borne & foliar disease problems. Ensure microbial solutions are locally adapted, accessible, and supported through region-specific advisory systems.

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