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PLANT-MICROBE INTERACTIONS UNDER A CHANGING CLIMATE: IMPLICATIONS FOR DISEASE DYNAMICS, BIOCONTROL EFFICACY, AND SUSTAINABLE AGRICULTURE

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Introduction

Plants do not exist in isolation; they are embedded within complex webs of interaction with the microorganisms that colonise their surfaces, tissues, and root zones. These interactions span the full spectrum from highly antagonistic - as in the case of necrotrophic and biotrophic plant pathogens - to mutually beneficial, as exemplified by nitrogen-fixing rhizobia, mycorrhizal fungi, and the diverse communities of endophytic bacteria and fungi that inhabit healthy plant tissues without causing disease. The balance of pathogenic and beneficial interactions within the plant microbiome is a key determinant of plant health, with implications that extend from individual crop yields to the broader functioning of terrestrial ecosystems.

Climate change is a cross-cutting driver that is simultaneously altering multiple dimensions of plant-microbe interactions. Rising mean temperatures and increasingly frequent extreme heat events affect the physiology of both plants and their associated microorganisms, often in ways that shift competitive advantages between hosts and pathogens. Altered precipitation patterns - including both drought and intense rainfall events - modify soil moisture regimes, splash dispersal of fungal conidia, and the water potential constraints on both pathogen germination and biocontrol agent activity. Elevated atmospheric CO_2 concentrations change plant physiology, altering the chemical composition of tissues and exudates that mediate interactions with microorganisms.

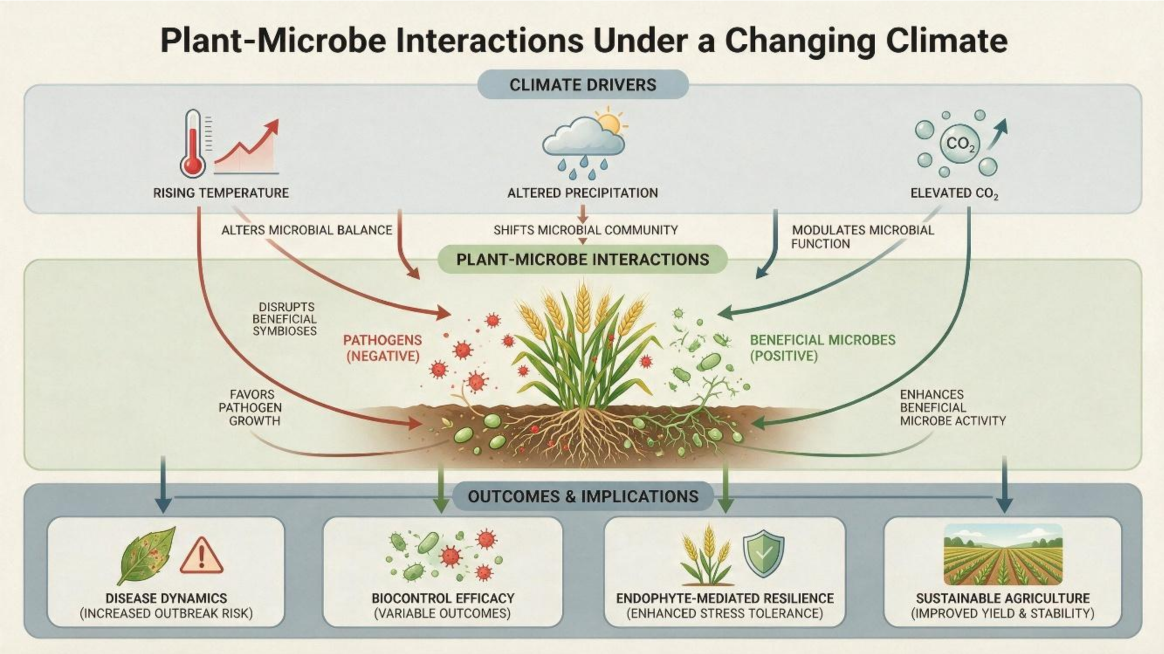

Fig. 1: Conceptual framework illustrating how climate-change drivers (rising temperature, altered precipitation, elevated CO_2) reshape plant-microbe interactions, shifting the balance between pathogenic and beneficial microbes and driving outcomes for disease dynamics, biocontrol efficacy, endophyte-mediated resilience, and sustainable agriculture.

Against this backdrop of environmental change, the need for robust, adaptive, and evidence-based approaches to plant disease management has never been more acute. This review integrates current evidence from plant pathology, microbial ecology, and climate science to examine how climate change is reshaping plant-microbe interactions and what strategies are available to maintain crop health under projected future conditions (Fig 1).

Climate Change and Plant Pathogen Distribution

Species Distribution Modelling Approaches

Species distribution modelling (SDM) tools, including maximum entropy modelling (MaxEnt), bioclimatic envelope models, and dynamic mechanistic models, have emerged as important instruments for projecting the geographic and temporal distribution of plant pathogens under current and future climate scenarios. These approaches use occurrence data for a given pathogen or vector combined with climatic predictor variables to identify the bioclimatic envelope within which the organism is able to establish and persist, and then project this envelope under future climate scenarios.

MaxEnt modelling has been applied to a range of plant disease systems with important outcomes for disease management planning. A recent analysis demonstrated that the distribution of pigeonpea sterility mosaic disease - one of the most economically important diseases of a critical legume crop in South Asia - is expected to undergo significant geographic shifts under projected climate change scenarios (Biradar et al., 2026). Such findings have direct implications for targeted surveillance, resistance breeding priorities, and the geographic deployment of biocontrol and chemical management resources. Such climate-driven changes in pathogen distribution and virulence align with the disease-dynamics pathway depicted in Fig. 1 & 2.

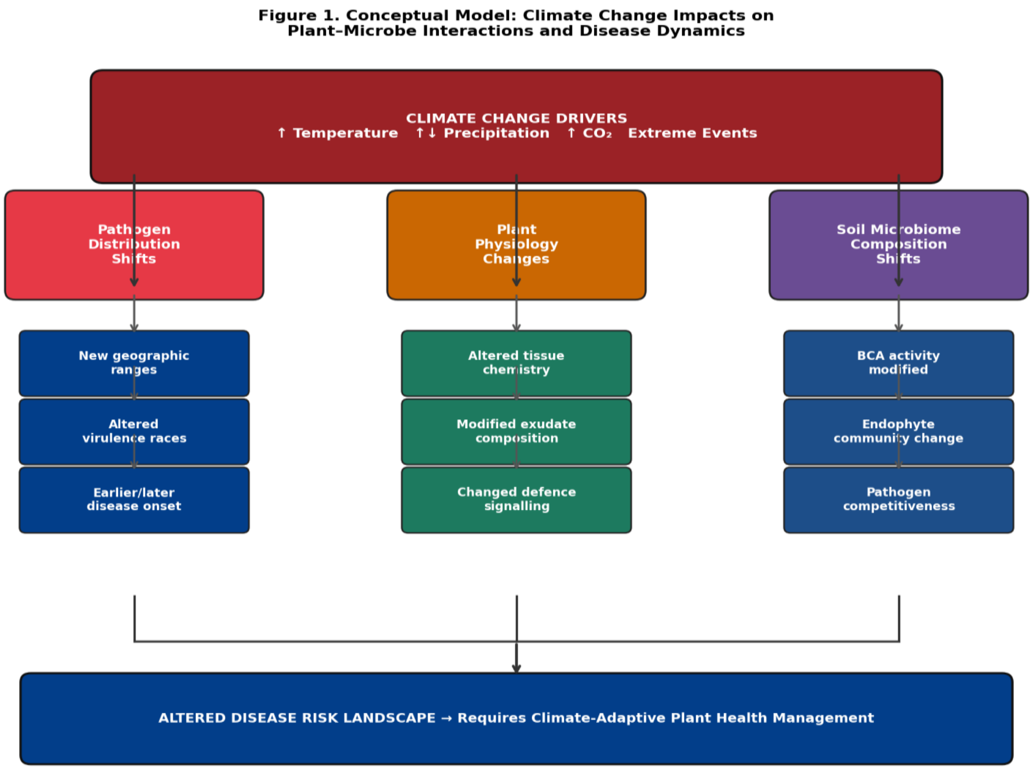

Fig. 2: Conceptual model depicting how climate change drivers cascade through three impact streams-pathogen distribution shifts, plant physiology changes, and soil microbiome composition shifts - to produce an altered disease risk landscape requiring adaptive plant health management.

Temperature and Precipitation Effects on Pathogen Virulence

Beyond distributional shifts, climate change may alter the virulence and aggressiveness of plant pathogens within their existing ranges. Temperature affects almost every aspect of pathogen biology including spore germination, infection efficiency, lesion expansion rate, sporulation capacity, and the duration of latent and infectious periods. For many foliar fungal pathogens, optimal temperatures for infection lie in the 20-30°C range, and further warming may in some cases reduce infection efficiency as temperatures exceed this optimum. However, warmer winters may increase the survival of pathogen inoculum and shift the timing of primary infections in temperate cropping systems (Fig 2). Fungicide efficacy - including that of fungicides evaluated against important leaf pathogens such as *Phyllosticta zingiberi* (Neha et al., 2021b) - may also be modulated by temperature and humidity conditions that affect both the activity of the fungicide molecule and the rate of pathogen development.

Climate Impacts on Biocontrol Agent Efficacy

Biological control agents (BCAs) - including antagonistic fungi such as *Trichoderma spp.* and plant growth-promoting bacteria such as *Bacillus subtilis* - are sensitive to the same environmental variables that affect plant pathogens. Temperature, soil moisture, pH, and UV irradiance all influence BCA survival, colonisation efficiency, and the production of key antimicrobial metabolites. Climate change may therefore alter the efficacy of biocontrol products that have been formulated and tested under specific environmental conditions. These environment-dependent effects on BCA performance correspond to the 'biocontrol efficacy' branch in Fig. 2.

The efficacy of Trichoderma-based biocontrol against tomato fruit rot pathogens has been documented under controlled laboratory conditions (Biradar *et al*., 2021a), demonstrating the *in vitro* potential of these organisms. However, translating laboratory-demonstrated efficacy to consistent field-level disease suppression remains challenging under stable climatic conditions, and this challenge may intensify as climate variability increases. Research is needed on the selection and formulation of BCA strains with high climate resilience - including thermotolerant Trichoderma strains that maintain efficacy across a wider temperature range - and on the development of climate-informed BCA application strategies that account for predicted weather conditions.

The interactions between BCAs and the broader soil and phyllosphere microbiome add further complexity to climate change impacts on biocontrol efficacy. Climate change alters microbial community composition in ways that may either enhance or diminish the competitive advantage of applied BCA strains. Multi-omics analysis of microbiome responses to climate variables - including the transcriptomic and metabolomic dimensions of endophyte-plant interactions (Biradar and Namrata, 2024) - is providing insights into the resilience of beneficial microbial associations under environmental stress.

Endophytes as Climate Resilience Mediators

Endophytic microorganisms - bacteria and fungi that colonise plant tissues without causing disease symptoms - are increasingly recognised as important mediators of plant responses to both biotic and abiotic stresses. Endophytes contribute to plant climate resilience through multiple mechanisms including the production of phytohormones (particularly abscisic acid, auxins, and cytokinins) that modulate stress responses, the synthesis of osmolytes that enhance drought tolerance, the production of volatile organic compounds that prime plant immunity, and the suppression of pathogenic microorganisms that might otherwise exploit stress-weakened plants. The role of endophytes in enhancing stress tolerance and suppressing disease reflects the 'endophyte-mediated resilience' component of Fig. 1 & 2.

The disease-suppressive potential of endophytes, including mechanisms of biocontrol relevant to major crop pathogens, has been extensively reviewed by Sahane *et al.* (2025), providing a comprehensive synthesis of the biological basis for endophyte-mediated plant protection. Advances in multi-omics characterisation of endophyte communities - including integrated genomic, transcriptomic, and metabolomic approaches - are revealing the full functional potential of these microorganisms and identifying key metabolites and genes responsible for stress resilience functions (Biradar and Namrata, 2024). These insights are enabling the targeted selection of endophyte strains for use as bioinoculants that enhance both disease resistance and climate resilience. The stability of endophyte communities under climate change is itself an important research question. Changes in temperature and precipitation alter the plant physiological status, tissue chemistry, and defence signalling pathways that shape endophyte community composition. Research on the responses of crop-associated endophyte communities to climate variables is needed to predict how endophyte-mediated disease suppression and climate resilience functions may change in coming decades.

Biotechnological Tools for Climate-Adaptive Disease Management

The development of crop varieties with durable resistance to multiple biotic stresses, capable of maintaining productivity under projected climate conditions, is a long-term imperative for sustainable agriculture. Biotechnological tools including CRISPR-Cas9 genome editing, RNA interference, and precision phenotyping technologies are accelerating progress toward this goal. The versatile application of CRISPR-Cas9 for biotic and abiotic stress management, including the targeted engineering of disease resistance through susceptibility gene disruption, has been comprehensively reviewed in the context of major and minor crops (Biradar *et al*., 2024). Such genomic tools, applied in conjunction with multi-omics-informed target identification, offer a pathway to the development of climate-smart crop varieties with broad-spectrum, durable disease resistance.

In the context of millet and other nutritionally important but research-underfunded crops, recent work has reviewed the application of modern biotechnological tools for disease resistance improvement (Patil *et al.,* 2025), demonstrating how the same molecular toolkit applied in major cereals can be adapted for use in nutritionally important minor crops where climate change is expected to exert the greatest impact on food security. Precision phenotyping tools including hyperspectral imaging are also relevant in this context, enabling the rapid characterisation of disease resistance in large breeding populations under both controlled and field conditions (Patil, 2025, Biradar *et al*.,2024).

Integrated Framework for Climate-Adaptive Plant Health Management

An integrated framework for managing plant-microbe interactions under climate change must incorporate: (i) ongoing surveillance and species distribution modelling to track shifts in pathogen distribution and seasonal dynamics; (ii) breeding and biotechnological programs to develop cultivars with durable, broad-spectrum disease resistance; (iii) development and deployment of climate-resilient biological control products; (iv) integrated endophyte management that harnesses naturally occurring beneficial microorganisms; (v) adaptive fungicide management that accounts for climate-driven changes in fungicide efficacy and resistance development risk; and (vi) extension and advisory systems that provide farmers with climate-informed disease management guidance.

The economic dimensions of climate-adaptive disease management must also be considered. Management interventions that are effective under current conditions may be economically suboptimal or impractical under future climate scenarios. Scenario-based economic analysis - evaluating the cost-effectiveness of alternative management strategies under multiple projected climate futures - is a valuable input to both research prioritisation and policy design. This multi-component strategy operationalises the pathways shown in Fig. 1, translating climate-driven shifts in plant–microbe interactions into actionable management levers.

Conclusion

Climate change is reshaping plant-microbe interactions in ways that create both new challenges and new opportunities for sustainable agriculture. Understanding and managing these interactions under a changing climate requires an unprecedented integration of epidemiological modelling (Biradar *et al*., 2026), microbial ecology, multi-omics (Biradar and Namrata, 2024), endophyte science (Sahane *et al*., 2025), biotechnology (Biradar *et al*., 2024; Patil *et al*., 2025), and precision agriculture technologies. The foundational knowledge generated by experimental studies on plant-pathogen interactions and management under current conditions (Biradar *et al*., 2021a; Neha *et al*., 2021b) provides essential reference points for tracking climate-driven changes. By embedding this knowledge within a systems-level framework that bridges scales from the molecular to the landscape and from the laboratory to the farm, the agricultural research community can develop the adaptive, climate-smart plant health management systems needed to sustain food security through the 21st century.

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