



Climate Variability and Its Influence on Plant Pathogen Interactions

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Introduction

Plant disease development has traditionally been framed through the disease triangle, which highlights the interaction among a susceptible host, a virulent pathogen, and a conducive environment (Debela *et al.*, 2018). Among these components, the environment is now undergoing rapid transformation due to climate change, significantly altering plant health dynamics worldwide (Das *et al.*, 2017).

Increasing temperatures, erratic precipitation patterns, prolonged droughts, elevated atmospheric CO₂ concentrations, and frequent extreme weather events are reshaping agro-ecosystems and redistributing disease risks (Das *et al.*, 2017). Rather than uniformly increasing disease incidence, climate change shifts pathogen distribution, enabling expansion into higher altitudes and latitudes while disrupting established disease calendars (Debela, 2018). Such variability challenges traditional forecasting systems and long-term predictive models (Miller *et al.*, 2022).

Climatic changes directly influence pathogen life cycles by shortening latent periods, enhancing sporulation, and accelerating epidemic development (Debela *et al.*, 2018). Altered rainfall affects spore dispersal, soil inoculum persistence, and bacterial transmission (Wolf *et al.*, 2018), while drought stress weakens plant defenses and increases susceptibility (Debela *et al.*, 2018). Conversely, excessive rainfall can create favorable canopy microclimates that trigger outbreaks (Fenta & Kebede, 2019). Elevated CO₂ further modifies host physiology, influencing photosynthesis, carbon–nitrogen balance, and defense metabolism, thereby reshaping host–pathogen interactions (Lal *et al.*, 2016).

Coupled with agricultural intensification, global trade, and fungicide resistance (Jeger *et al.*, 2021), these changes are transforming plant diseases into more dynamic and uncertain threats. Understanding these interactions is essential for developing resilient cropping systems and sustainable management strategies (Lahlali *et al.*, 2024).

Climate Drivers Changing Plant Disease Systems

Climate change is fundamentally altering plant disease dynamics by modifying temperature, rainfall patterns, atmospheric CO₂ levels, and the frequency of extreme weather events (Hossain *et al.*, 2024). Rising temperatures

accelerate pathogen growth, shorten disease cycles, and shift pathogens into new geographic regions, including higher altitudes and latitudes (Debela *et al.*, 2018). However, responses vary depending on each pathogen’s temperature optimum (Jeger *et al.*, 2021).

Changes in rainfall and humidity influence leaf wetness and soil moisture, affecting spore germination, dispersal, and survival of both foliar and soil-borne pathogens (Silva *et al.*, 2024). Drought can weaken plant defenses (Debela *et al.*, 2018), while intense rainfall and flooding promote sudden outbreaks (Fenta & Kebede, 2019).

Elevated CO₂ alters plant physiology by increasing biomass and modifying carbon–nitrogen balance and defense pathways, leading to complex and pathosystem-specific effects on disease susceptibility (Debela, 2018).

Extreme events such as heat waves, storms, and floods further trigger unpredictable epidemic outbreaks and can disrupt beneficial soil microbial communities. Together, these climate drivers are reshaping plant disease patterns and increasing the risk of emerging and re-emerging diseases (Hossain *et al.*, 2024).

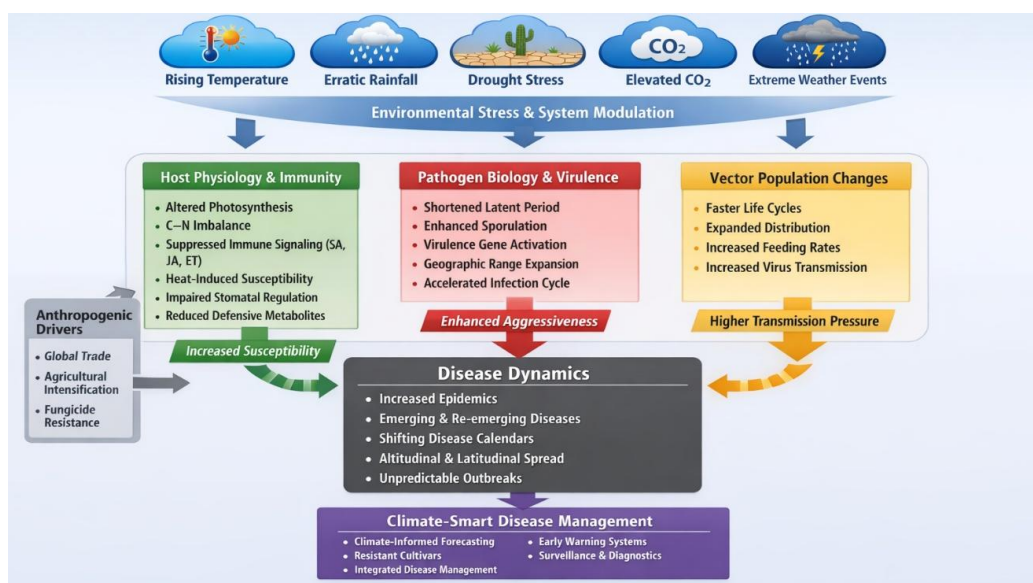


Figure 1. Integrated Conceptual Framework of Climate Variability Influencing Plant- Pathogen Interactions

Climate variability not only alters environmental conditions but also modifies biological interactions at molecular and physiological levels within the plant–pathogen system (Son & Park, 2022). Fluctuating temperatures and moisture regimes influence plant immune signaling pathways, including salicylic acid, jasmonic acid, and ethylene-mediated defenses. Heat stress, for instance, may suppress immune gene expression and lead to “heat-induced susceptibility,” where plants become more vulnerable to infection despite the absence of major genetic changes. Similarly, drought stress can impair stomatal regulation and reduce the production of defensive metabolites,



weakening resistance against both foliar and soil-borne pathogens. On the pathogen side, climatic fluctuations can regulate virulence gene expression, spore production, and infection efficiency (Waheed *et al.*, 2023). In vector-borne diseases, temperature variability can also accelerate insect life cycles, increase feeding frequency, and expand vector distribution, thereby intensifying virus transmission dynamics (Das *et al.*, 2017). These multilayered interactions demonstrate that climate variability operates not only at ecosystem scales but also at cellular and molecular levels (Hossain *et al.*, 2024). The integrated effects of climate variability on host, pathogen, and vector interactions are summarized in Figure 1.

Several recent observations illustrate the practical consequences of climate-driven shifts in plant disease dynamics. The expansion of rust diseases into higher altitudes and previously cooler regions reflects warming trends that favor pathogen establishment in new agro-ecological zones (Miller *et al.*, 2022). Increased humidity and erratic rainfall have been linked to more frequent outbreaks of late blight and other foliar fungal diseases (Das *et al.*, 2017). In semi-arid regions, rising temperatures combined with intermittent drought have intensified the incidence of vascular wilts and root rot pathogens (Singh *et al.*, 2023). Likewise, variability in rainfall distribution has influenced the epidemiology of rice blast and other moisture-sensitive diseases. These examples highlight how climate variability reshapes regional disease burdens and creates unexpected epidemic patterns (Jeger *et al.*, 2021).

The growing instability of climatic conditions poses significant challenges for plant disease forecasting and management (Miller *et al.*, 2022). Traditional prediction models based on historical climate patterns are becoming less reliable under rapidly changing environmental conditions. As a result, there is increasing emphasis on climate-informed early warning systems that integrate real-time weather data, remote sensing, and predictive modeling tools (Hossain *et al.*, 2024). Breeding programs are also shifting toward the development of climate-resilient varieties with durable and broad-spectrum resistance (Son & Park, 2022). Integrated Disease Management strategies must now consider climate variability as a central factor, combining resistant cultivars, biological control, cultural practices, and judicious chemical use (Jeger *et al.*, 2021). Strengthening surveillance systems and rapid diagnostic tools is equally important to detect emerging pathogens before large-scale outbreaks occur (Wang *et al.*, 2024).

In conclusion, climate variability is reshaping plant–pathogen interactions in complex and often unpredictable ways (Jeger *et al.*, 2021). By influencing host physiology, pathogen biology, vector behavior, and agro-ecosystem stability, it increases uncertainty in disease occurrence and severity (Singh *et al.*, 2023). Addressing these challenges requires a shift toward climate-smart plant pathology that integrates ecological understanding, technological innovation, and multidisciplinary collaboration (Jeger *et al.*, 2021). Strengthening adaptive research, surveillance, and resilient cropping systems will be essential to safeguard agricultural productivity and global food security in an era of accelerating climatic change (Wang *et al.*, 2024).



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