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Fungal Plant Pathogens under Climate Change: Emerging Diseases, Epidemiological Shifts, Host–Pathogen Interactions and Sustainable Disease Management

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ABSTRACT

Climate change is fundamentally altering the ecological and epidemiological relationships between plants and fungal pathogens. Increasing temperatures, altered precipitation patterns, elevated atmospheric carbon dioxide, drought, extreme weather events and changing seasonal dynamics can influence fungal growth, reproduction, dispersal, survival, host susceptibility and disease development. These environmental changes are contributing to shifts in the geographical distribution, seasonal occurrence and intensity of several fungal plant diseases while creating opportunities for pathogens to colonize new hosts and environments. Climate-driven changes in plant physiology and immunity may further increase susceptibility to infection, particularly when plants experience simultaneous abiotic and biotic stresses. Fungal pathogens can respond rapidly to environmental changes through physiological plasticity, genetic adaptation and shifts in population structure, potentially generating new disease risks for agricultural production. Changes in temperature and moisture can also influence infection cycles, spore production, overwintering, pathogen evolution and the effectiveness of conventional disease-management practices. Consequently, traditional disease-control strategies based primarily on historical climatic patterns may become less reliable under future environmental conditions. Sustainable management requires integration of resistant cultivars, biological control, improved cultural practices, precision irrigation, disease forecasting, molecular diagnostics, integrated pest and disease management, and climate-resilient agricultural systems. Advances in genomics, transcriptomics, remote sensing, artificial intelligence and epidemiological modelling provide new opportunities for predicting disease emergence and developing adaptive management strategies. This review examines the influence of major climate variables on fungal plant pathogens, mechanisms underlying climate-driven disease emergence, epidemiological shifts, host–pathogen interactions, pathogen adaptation and sustainable approaches for managing fungal diseases under changing climatic conditions.

Keywords: *climate change, fungal pathogens, plant diseases, disease epidemiology, emerging diseases, host–pathogen interactions, pathogen adaptation, crop protection, disease forecasting, sustainable agriculture*

1. Introduction

Agricultural ecosystems are highly sensitive to climatic variability because crop productivity depends on interactions among temperature, precipitation, soil conditions, atmospheric composition and biological communities. Among the biological factors affecting crop production, fungal pathogens are particularly important because of their diversity, environmental responsiveness and capacity to evolve rapidly. Fungal diseases can reduce yield, compromise product quality and increase production costs, while severe epidemics can threaten food security at regional and global scales [1-2]. Climate change is modifying the environmental conditions under which plant pathogens interact with their hosts. Global warming is accompanied by changes in rainfall distribution, humidity, drought frequency, extreme temperatures, atmospheric carbon dioxide and the timing of seasonal events. These changes can influence nearly every stage of the plant disease cycle, including pathogen survival, spore germination, infection, colonization, reproduction, dispersal and overwintering [3]. The relationship between climate and plant disease is not linear. A moderate increase in temperature may accelerate pathogen development in one system while reducing disease severity in another if temperatures exceed the pathogen's optimum. Similarly, drought may reduce foliar disease by limiting moisture required for spore germination but may increase susceptibility by weakening host physiological defenses. Consequently, climate change should be considered a multidimensional driver of disease rather than simply a process of temperature increase.

Fungal pathogens may also respond evolutionarily to climate change. Populations exposed to new environmental conditions can undergo selection for increased thermal tolerance, altered reproductive timing, changes in host range or modifications of virulence. Pathogens with short generation times, high reproductive rates and substantial genetic variation may adapt particularly rapidly.

At the same time, crops are experiencing climate-associated physiological stress. Heat, drought, flooding and nutrient imbalance can alter plant metabolism, stomatal behavior, cell-wall properties, hormone signaling and immune responses.

A plant experiencing simultaneous abiotic and biotic stresses may respond differently from a plant exposed to pathogens under optimal conditions [4]. Climate change can also affect the geographical distribution of pathogens. Warmer temperatures may allow some pathogens to survive in regions that were previously unsuitable, while changes in precipitation can establish new disease-favorable environments. Changes in crop production systems may further facilitate pathogen movement [5]. These developments have major implications for agricultural disease management. Historical disease calendars and fixed recommendations may become less reliable when pathogen emergence and infection periods shift. Sustainable disease management therefore requires dynamic surveillance, climate-informed forecasting, resistant crop varieties, biological control and adaptive agronomic practices.

2. Climate Variables Influencing Fungal Plant Diseases

Several climatic variables directly or indirectly influence fungal pathogens and their hosts.

2.1 Temperature

Temperature is one of the most important determinants of fungal growth, sporulation, germination and infection. Each pathogen possesses a characteristic minimum, optimum and maximum temperature range. Small changes around the optimum can substantially alter disease development [6]. Increasing temperatures may shorten pathogen generation times and accelerate infection cycles. However, excessive heat can inhibit fungal growth or reduce spore viability. The impact therefore depends on the thermal biology of both the pathogen and host. Temperature also influences plant physiology. Heat stress can alter photosynthesis, respiration, membrane stability and hormone signaling, potentially modifying host susceptibility.

2.2 Precipitation and Humidity

Water availability is essential for many fungal infection processes. Rainfall can promote spore production, dispersal and germination, while high relative humidity provides favorable conditions for infection [7]. Changes in rainfall patterns can therefore alter disease epidemics even when total annual precipitation remains relatively stable. Longer periods of rainfall followed by warm temperatures may create particularly favorable conditions for rapidly developing epidemics [8]. Conversely, prolonged drought may suppress pathogens that require free water but can weaken plants and increase susceptibility to soilborne pathogens.

2.3 Atmospheric Carbon Dioxide

Elevated atmospheric CO_2 can modify plant architecture, carbon allocation, stomatal conductance, tissue chemistry and nutrient composition. These changes may influence host–pathogen interactions [9]. The response of fungal pathogens to elevated CO_2 is variable. Some pathogens may benefit indirectly from increased host biomass, whereas changes in leaf chemistry or stomatal behavior may reduce infection by others.

2.4 Extreme Weather Events

Heatwaves, floods, cyclones, storms and sudden temperature fluctuations can influence disease dynamics in complex ways. Storms can physically damage plant tissues, creating infection sites, while flooding can facilitate dispersal of soilborne pathogens [10]. Extreme events can also disrupt agricultural management and delay fungicide applications, harvesting or field sanitation.

Table 1. Major climatic factors affecting fungal plant diseases

Climate factor	Effect on pathogen	Effect on host	Potential disease consequence
Increased temperature	Alters growth, sporulation and infection rate	Heat stress and altered immunity	Shifts in disease intensity and distribution
Increased humidity	Promotes spore germination	Prolonged leaf wetness	Increased foliar disease
Altered rainfall	Changes dispersal and infection conditions	Water stress or flooding	Variable epidemic development
Drought	Suppresses some fungi but favors others	Weakens physiological defenses	Increased susceptibility in some systems
Elevated CO_2	Alters pathogen–host interactions	Changes carbon allocation and tissue chemistry	Pathogen-specific disease responses
Heatwaves	May exceed fungal thermal limits	Severe cellular stress	Reduced or increased disease depending on system
Flooding	Enhances movement of some soilborne pathogens	Root oxygen deficiency	Increased root and vascular diseases

3. Climate Change and Fungal Pathogen Biology

Climate change can influence fungal pathogens at multiple biological levels. Higher temperatures may accelerate enzymatic reactions, mycelial growth and spore production until physiological thresholds are reached. Changes in humidity influence the viability and dispersal of spores. Altered precipitation affects the availability of water required for infection. The timing of reproductive events is also climate-sensitive. Earlier seasonal warming may cause pathogens to produce spores earlier, potentially desynchronizing traditional disease-management schedules. Changes in overwintering conditions are especially important for perennial crops and temperate agricultural systems. Warmer winters may improve pathogen survival, increasing inoculum availability during subsequent growing seasons [10].

Climate change can also influence pathogen–vector interactions when fungal diseases depend on insect or other biological vectors. Changes in vector distribution can indirectly modify pathogen transmission.

4. Emerging and Re-Emerging Fungal Diseases

Climate change can contribute to disease emergence through several pathways:

- Expansion into new geographical regions.
- Increased survival during unfavorable seasons.
- Changes in host susceptibility.
- Altered pathogen reproductive cycles.
- Introduction of pathogens into newly suitable environments.
- Increased frequency of host stress.
- Changes in cropping systems.

- Increased interaction between previously separated host and pathogen populations.

Emergence does not necessarily mean that a pathogen is completely new. A previously minor pathogen may become economically important when climatic conditions shift in its favor [11]. Pathogens can also become problematic in crops or regions where they were previously uncommon. Such events create challenges because farmers and extension systems may lack established surveillance and management protocols.

5. Geographic Shifts in Pathogen Distribution

The geographical range of a pathogen depends on temperature, moisture, host availability and other ecological conditions. Climate change may modify the suitability of regions for pathogen establishment. Warmer conditions can permit some pathogens to expand toward higher latitudes or elevations. However, range expansion is not universal because pathogens may also encounter barriers such as unsuitable humidity, absence of hosts, competition with other microorganisms or excessive temperatures [12]. Agricultural trade and human movement can accelerate the geographic spread of pathogens once environmental conditions become suitable. The interaction between climate-driven environmental suitability and anthropogenic dispersal can therefore increase disease emergence risks.

6. Altered Disease Epidemiology

Plant disease epidemics are traditionally described through interactions among host, pathogen and environment. Climate change modifies the environmental component while simultaneously affecting the host and pathogen [13]. The disease triangle therefore becomes increasingly dynamic under climate change. Temperature and moisture influence infection rates, while host stress and pathogen adaptation modify the biological components.

Table 2. Climate-driven epidemiological changes

Epidemiological component	Climate-driven change	Consequence
Primary inoculum	Increased overwintering survival	Earlier disease initiation
Infection period	Altered temperature and leaf wetness	Longer or shorter infection windows
Sporulation	Changed humidity and temperature	Altered secondary inoculum
Pathogen generation time	Increased under favorable warming	Faster epidemics
Geographic range	Changing environmental suitability	Emergence in new regions
Host susceptibility	Increased abiotic stress	Greater disease severity
Disease forecasting	Changing environmental thresholds	Need for dynamic models

7. Climate Change and Host Susceptibility

Climate affects not only the pathogen but also the plant. Heat and drought can alter plant carbon allocation, nutrient status, membrane stability and hormone signaling. Water stress may cause stomatal closure, reduced photosynthesis and altered defense metabolism. Severe stress can compromise the ability of plants to produce antimicrobial compounds and structural barriers. Flooding creates another form of stress [14]. Oxygen deficiency in roots can alter metabolism and weaken root tissues, potentially increasing vulnerability to soilborne pathogens. Combined stresses are particularly important. A plant exposed simultaneously to heat and pathogen infection may show defense responses that differ substantially from those observed under pathogen attack alone. This has important implications for breeding. Disease resistance should increasingly be evaluated under realistic combinations of temperature, water availability and pathogen pressure.

8. Host–Pathogen Interaction under Changing Climate

The outcome of infection is determined by continuous molecular communication between host and pathogen. Climate change can modify this communication by affecting gene expression, metabolism, hormone signaling and effector activity. Fungal pathogens secrete effectors that manipulate plant processes, while plants detect pathogen-associated molecules and activate defense pathways. Environmental stress can modify both sides of this interaction [15]. Temperature-sensitive resistance genes are particularly important. A resistance mechanism effective under one temperature regime may become less effective when temperatures change. Similarly, fungal effectors may have temperature-dependent expression or activity [16]. Therefore, climate-resilient disease resistance requires understanding the interaction between resistance mechanisms and environmental conditions.

9. Pathogen Evolution and Adaptation

Climate change creates new selective pressures for fungal populations. Pathogens may respond through phenotypic plasticity, genetic mutation, recombination, gene flow and selection [17]. Populations repeatedly exposed to higher temperatures may experience selection for thermal tolerance. Similarly, changes in host distribution may favor pathogen genotypes capable of infecting new cultivars or host species. Pathogen adaptation may occur particularly rapidly in species with short generation times and high reproductive capacity. The evolutionary response can make previously effective resistance genes less durable.

Table 3. Potential pathogen adaptations to climate change

Adaptation	Possible mechanism	Agricultural implication
Thermal tolerance	Genetic selection and physiological acclimation	Expansion into warmer regions
Altered sporulation	Changes in reproductive regulation	Modified epidemic timing
Host-range expansion	Genetic variation and selection	Emergence on new crops
Altered virulence	Effector and regulatory evolution	Breakdown of resistance
Changed overwintering	Physiological adaptation	Increased early-season inoculum
Phenotypic plasticity	Flexible gene expression	Rapid environmental response

10. Climate Change and Soilborne Fungal Pathogens

Soilborne diseases are strongly influenced by temperature, soil moisture, organic matter and microbial community structure [18]. Changes in precipitation and irrigation can modify soil moisture and oxygen availability. Excessive moisture can favor pathogens associated with root and crown diseases, whereas drought may weaken roots and alter microbial competition. Soil temperature also affects pathogen growth and survival. Warmer soils may accelerate disease development in some systems while reducing pathogen viability in others. Changes in soil microbial communities can further influence disease suppression. Beneficial microorganisms may decline or increase depending on environmental conditions, thereby altering the balance between pathogens and antagonists.

11. Climate Change and Foliar Fungal Diseases

Foliar pathogens are particularly sensitive to humidity, temperature and leaf-wetness duration. Many require extended periods of moisture for spore germination and penetration. Changes in rainfall frequency and humidity can therefore alter epidemic development. Increased frequency of warm and humid periods may promote repeated infection cycles. Conversely, increased heat without adequate moisture may suppress certain foliar pathogens. Disease risk should therefore be assessed using pathogen-specific environmental thresholds rather than assuming that warming universally increases fungal diseases.

12. Mycotoxins and Food Safety under Climate Change

Climate change may influence not only plant disease but also contamination of agricultural commodities with fungal secondary metabolites. Certain mycotoxin-producing fungi are favored by particular combinations of temperature, moisture and plant stress. Drought, insect damage and heat stress can predispose crops to fungal colonization and subsequent toxin accumulation. Mycotoxins such as aflatoxins, fumonisins, trichothecenes and ochratoxin-related compounds are important food-safety concerns. Climate-driven shifts in fungal ecology may alter the geographical and seasonal distribution of mycotoxin risks. Consequently, climate-resilient crop protection should integrate disease management with post-harvest monitoring and food-safety surveillance.

13. Climate Change, Crop Intensification and Disease Pressure

Changes in cropping systems can interact with climate change. Intensive monoculture, reduced crop diversity, inadequate residue management and excessive nitrogen inputs can increase disease pressure under favorable environmental conditions. Warmer climates may also encourage cultivation of crops in new regions. Introduction of a susceptible crop into a pathogen-rich environment can increase disease risk [18]. Diversified cropping systems, crop rotation and improved soil management can reduce pathogen inoculum and improve ecosystem resilience.

14. Biological Control under Climate Change

Beneficial microorganisms provide an important alternative to exclusive dependence on chemical fungicides. Fungal and bacterial biocontrol agents can suppress pathogens through competition, antibiosis, parasitism and induced resistance [19]. Important examples include *Trichoderma*, *Bacillus*, *Pseudomonas* and beneficial mycorrhizal fungi.

However, climate change can influence the performance of biological control agents. Temperature, humidity, soil moisture and microbial competition affect their establishment and activity. Future biocontrol research should therefore prioritize strains with broad environmental tolerance and stable performance under fluctuating climatic conditions.

15. Integrated Disease Management under Climate Change

Integrated disease management (IDM) is particularly important under changing climatic conditions because no single intervention can reliably control emerging disease risks. An adaptive IDM framework should combine host resistance, cultural practices, biological control, chemical protection, monitoring and forecasting.

17. Disease Forecasting and Early Warning Systems

Climate-informed disease forecasting can substantially improve the efficiency of disease management. Forecasting systems integrate pathogen biology with temperature, humidity, rainfall and leaf-wetness data[20]. Modern systems increasingly incorporate remote sensing, weather stations, satellite observations and machine-learning algorithms. These technologies can identify environmental conditions favorable for infection before visible symptoms appear. Early warning systems can help farmers optimize fungicide applications and reduce unnecessary treatments. They may also support regional surveillance for emerging pathogens.

18. Remote Sensing and Precision Agriculture

Remote sensing technologies provide new opportunities for detecting fungal diseases over large agricultural areas. Hyperspectral imaging can identify changes in leaf reflectance associated with infection before symptoms become visually obvious. Thermal imaging can detect changes in transpiration and canopy temperature, while multispectral imaging can provide information about vegetation stress. Unmanned aerial vehicles can collect high-resolution images for disease mapping. When integrated with pathogen diagnostics and weather data, these technologies can support precision disease management. Artificial intelligence can further improve disease recognition by identifying complex patterns in large image datasets.

19. Molecular Diagnostics and Pathogen Surveillance

Rapid molecular diagnostics are increasingly important for detecting emerging fungal pathogens. Conventional isolation and morphological identification can require substantial time and expertise. PCR, quantitative PCR, loop-mediated isothermal amplification, DNA sequencing and metagenomic approaches can provide faster and more specific identification. Pathogen surveillance should increasingly incorporate genomic monitoring to detect changes in virulence, fungicide sensitivity and geographic distribution. Early identification of emerging pathogen populations can support rapid deployment of management measures.

20. Fungicide Use and Resistance Management

Chemical fungicides remain important components of fungal disease management, but their effectiveness can be compromised by pathogen resistance. Climate change may alter fungicide performance through temperature-dependent metabolism, degradation and pathogen growth rates. Increased disease pressure may also increase fungicide use, intensifying selection for resistant pathogen populations.

Integrated resistance-management strategies should include rotation of fungicides with different modes of action, appropriate application timing, use of mixtures where scientifically justified and integration with nonchemical approaches [19]. The goal should be to maintain fungicide efficacy while reducing environmental and evolutionary risks.

21. Sustainable Soil and Crop Management

Healthy agricultural soils can contribute to natural disease suppression. Organic matter management, crop rotation, reduced soil disturbance, balanced fertilization and microbial diversity can influence pathogen populations. Excessive nitrogen can sometimes increase susceptibility to fungal diseases by promoting succulent growth or altering plant defense chemistry. Balanced nutrient management is therefore important. Cover crops and diversified rotations can modify soil microbial communities and reduce the buildup of host-specific pathogens.

25. Conclusion

Climate change is reshaping plant–fungus interactions by modifying pathogen biology, host susceptibility, disease epidemiology and agricultural environments. Temperature increases, altered precipitation, humidity changes, drought, flooding, elevated atmospheric CO_2 and extreme weather events can alter fungal growth, reproduction, dispersal and survival while simultaneously affecting plant defense and physiological resilience. These changes may shift the geographical distribution and seasonal dynamics of fungal diseases and create opportunities for emerging and re-emerging pathogens. Pathogen populations may also adapt through phenotypic plasticity and evolutionary change, increasing uncertainty regarding future disease risks. Sustainable management therefore requires a transition from static disease-control strategies toward dynamic, climate-informed approaches. Resistant cultivars, biological control, integrated disease management, soil health improvement, precision irrigation, molecular diagnostics, remote sensing and disease forecasting should be integrated according to local epidemiological conditions. Advances in genomics, microbiome science, artificial intelligence and predictive modelling offer new opportunities for anticipating disease emergence and developing climate-resilient agricultural systems. Ultimately, successful management of fungal plant diseases under climate change will depend on integrating pathogen biology, host resistance, environmental monitoring and sustainable agricultural practices within adaptive disease-management frameworks.

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