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## Impact of Climate Change and Global Warming in Fungal Plant Diseases and its Emerging Threats and Adaptive Strategies: A Review

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### ABSTRACT

Climate change and global warming are significantly impacting fungal plant diseases. It is posing a serious threat to global food security. The rising temperature, altered precipitation patterns, increased humidity, and elevated atmospheric CO<sub>2</sub> create favorable conditions for fungal growth and infection. Plant-associated fungi perform key roles in managing nitrogen transformation in soils, ensuring nutrient availability for plants, and supporting plant health and development. These mechanisms are significantly altered by abiotic stresses resulting from climate change. This situation presents emerging threats such as increased mycotoxin contamination, new diseases, and reduced effectiveness of fungicides. Temperature variations produce molecular-level changes in pathogenesis. The adaptive strategies to mitigate impacts include developing resistant crop varieties, implementing integrated pest management, and promoting sustainable agriculture. The complex interactions between climate change and fungal plant diseases are crucial for developing effective strategies to protect crops and ensure food security in a changing world. This review



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examines the multifaceted impact of climate change on fungal plant diseases, including increased disease incidence, severity, ranges of pathogens, altered host susceptibility, and greater pathogen diversity.

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## INTRODUCTION

Climate change is profoundly affecting fungal plant diseases by modifying pathogen behavior and host vulnerability, resulting in new threats and necessitating adaptive solutions. Elevated temperatures, modified precipitation patterns, and extreme meteorological phenomena foster circumstances conducive to fungal proliferation, dissemination, and pathogenicity. The United Nations Intergovernmental panel on climate change (IPCC) research predicts that carbon dioxide levels will stabilize approximately 45% above current levels, a threshold deemed hazardous by the IPCC (IPCC, 2007). The rising temperatures, unpredictable rainfall, and shrinking irrigated soil water tables may result in a 40% loss in agricultural productivity in South Asian countries, including India, by 2100 (IPCC 2008). The IPCC projected at a recent summit that global temperatures will increase by 1.5°C to 4.8°C by the end of the century (IPCC, 2014). The reports highlight the critical need to tackle climate change immediately, with some predicting that the globe would briefly surpass the 1.5°C warming barrier in 2024 (IPCC, 2024). Human actions are causing climate change in global temperatures, CO<sub>2</sub> levels in the air, rainfall patterns, and the number of extreme weather events that happen. Climate change is changing plant-pathogen interactions, with major implications for global agriculture systems (Kumar, Deepak, and Ria Mukhopadhyay, 2025). Climate change affects agricultural production systems through both direct and indirect mechanisms. Fluctuations in physical activities, including ambient air temperature, seasonal distributions, and water availability, directly influence agricultural productivity (Abbas et al., 2022; Al-Tawaha et al., 2020; Ray et al., 2019; Shrestha, 2019; Zhao et al., 2017; Verma, Song, Lin, et al., 2021; Verma, Song, Zeng, et al., 2021). Paleoclimatic trends have been noted to influence agricultural productivity variably among sites, exhibiting detrimental consequences relative to beneficial benefits (Bajwa et al., 2020, Khan et al., 2023, Ray et al., 2015). The positive impact of increased atmospheric CO<sub>2</sub> on plant growth, including enhanced photosynthetic responses and improved water efficiency, is generally being observed. The influence of climate change on crop development is contingent upon several climatic parameters, including temperature, precipitation patterns, and atmospheric CO<sub>2</sub> levels (Verma, Krishan K., et al., 2022). Examine the alterations in the growth, reproduction, sporulation, and other phases of the life cycle of diverse pathogens. Our molecular comprehension of modifications in the mechanisms of plant-pathogen



interactions resulting from global warming ,and the disease risk models developed to predict pathogen behaviour under changed climatic conditions (Kumar, Deepak, and Ria Mukhopadhyay,2025).

### **Fungal pathogen**

Climate change is modifying the dynamics among plants,diseases,and the environment,with profound consequences for global food security,forestry,and ecosystems.Rising temperatures,altered precipitation patterns,elevated atmospheric CO<sub>2</sub> levels,and a higher incidence of fungal plant diseases.These alterations are exacerbating the intensity of epidemics,altering mycotoxin hazards,and complicating fungicide efficacy and host resistance.Climate change can modify fungal diversity, distribution, and activity. Elevated temperatures and augmented precipitation in certain areas may enhance fungal breakdown rates ,thereby improving soil fertility and potentially increasing plant productivity.The effects of climate change are similar to those of a geographical dragging, since they disturb established mycorrhizal communities and favour opportunistic species that have the potential to become invasive.This reorganization may result in partnerships that are less effective, may have an effect on the growth of plants, and may make ecological imbalances more likely( Mridu, N. S., and J. Kumar(2024).Mechanisms range from effects on pathogen life cycles, host physiology, and immunity, to vector ecology, and the plant microbiome.Adaptive approaches,including climate-smartIPM,durable resistance breeding,microbiome-informed biocontrol,and predictive early-warming systems,and the role of emerging technologies for managing global threat.Filling the knowledge gaps in india,and modelling and experimentation,including crucial to securing continued food production and biodiversity under ongoing warming.Fungal diseases represent one of the most devastating biotic stressors for agriculture productivity across the globe, resulting in estimated annual yield loss of 10–23% in major crop species (Savary, Serge, et al. 2019).Changes in the climate such as long-term warming, shifts in precipitation patterns, rising concentrations of CO<sub>2</sub>, and more frequent climate extremes— exacerbate these threats (Chakraborty and Newton, 2011; IPCC, 2022).These drivers modify the disease triangle(host, pathogen, and environment), and affect epidemiology and management outcomes(Garrett, Karen A., et al,2006).It expands the thermal niche of most pathogens. For instance, *Puccinia striiformis* (yellow rust) has been predicted to increase in expansion in Europe as a result of warmer winters (Milus, Eugene A., Kristian Kristensen, and Mogens S. Hovmoller,2009). By the contrary, extreme hot temperatures could overcome pathogen optima but also weaken host defense(Luck, Jo, et al.,2011).Differences in precipitation and relative humidity affect the duration of leaf wetness, which is critical for folige pathogens such as



*Phytophthora infestans* and *Botrytis cinerea*(Gossen, Bruce D.,and Zhiwen Lan.2021). During a drought, the plant is predisposed to vascular wilts (*Fusarium oxysporum*, *Verticillium dahliae*)(El-Khallal, Samia M. 2007).Increasing CO<sub>2</sub> makes the canopy dense and alters microclimates conducive to leaf pathogens(Zayan, Sahar Abdou,2019). Ozone stress weaken the plants defensive complex thus making them liable to attack by necrotrophs (Agrios, 2005).Storms and floods promote the long-distance spread of spores, whilst drought–rewet offer the flush of inoculum(Garrett,Karen A.,et al.2006).Alterations in host immunity and microbiomes under stress conditions modify the resistance levels (Guzmán-Guzmán, Paulina, et al. 2023).The impact of climate change is negative on biodiversity of beneficial antagonists such as *Trichoderma spp.*and *Bacillus spp.*(poveda,jorge,2021).

### List of fungal plant pathogen and impact of climate change

| S.N<br>O | Pathogen   | Host             | Climate Change Impact   | Reference                                 |
|----------|--|------------------|---|---|
| 1        | <i>Puccinia striiformis</i><br><i>f.sp.tritici</i> (Wheat<br>yellow rust)    | Wheat            | Milder winters and warmer springs enhance survival and aggressiveness,poleward spread in europe and asia    | Milus et al., 2009                        |
| 2        | <i>Puccinia graminis</i> f.<br>sp. <i>tritici</i> (Wheat<br>stem rust, Ug99) | Wheat,<br>barley | Climate driven spread risk; warmer conditions favor survival of alternate hosts and urediniospore viability | Afzal,<br>Amir, et al(2015)               |
| 3        | <i>Hemileia vastatrix</i><br>(Coffee leaf rust)                              | Coffee           | Epidemics linked to warmer nights and rainfall shifts in Central America                                    | Avelino,<br>Jacques, et al., 2015         |
| 4        | <i>Magnaporthe oryzae</i><br>(Rice blast)                                    | Rice             | More conducive under warm, humid climates; extended epidemic seasons  | Yan, Xia, and<br>Nicholas J. Talbot.,2016 |
| 5        | <i>Magnaporthe oryzae</i><br>pathotype Triticum<br>(Wheat blast)             | Wheat            | Spread to Asia facilitated by warm, humid climates  | Ceresini, paulo cezar, et<br>al(2019).    |
| 6        | <i>Blumeria graminis</i>   | Wheat,           | Expanded risk under mild winters  | Bebber, Daniel P.,                        |



|    |  |                            |  |   |
|----|--|----------------------------|--|---|
|    | (Powdery mildew)   | barley,<br>cereals         | and longer growing seasons   | Mark AT Ramotowski, and Sarah J. Gurr(2013).  |
| 7  | <i>Fusarium oxysporum</i> f. sp. <i>lycopersici</i><br>(Fusarium wilt) | Tomato                     | More severe under drought and high soil temperatures; interacts with nematodes | El-Khallal, Samia M. 2007                     |
| 8  | <i>Verticillium dahliae</i><br>(Verticillium wilt)                     | Tomato, cotton, olive      | More damaging under water-stressed conditions; persistence in soils extended   | Inderbitzin Patrik, et al. 2011,              |
| 9  | <i>Phytophthora infestans</i> (Late blight)                            | Potato, tomato             | Epidemics influenced by increased humidity, extended rainy periods             | Maurya, Manoj Kumar, et al.2025               |
| 10 | <i>Phytophthora cinnamomi</i>  | Forest trees, avocado      | More severe with wetter winters and flooding                                   | Appelgryn, Elrea(2014)                        |
| 11 | <i>Botrytis cinerea</i><br>(Gray mold)                                 | Grapes, fruits, vegetables | Enhanced by fluctuating temperatures and high humidity                         | Mahmoud, Mohannad, et al.(2023)               |
| 12 | <i>Aspergillus flavus</i> & <i>A. parasiticus</i><br>(Aflatoxins)      | Maize, groundnut           | Drought and heat stress increase aflatoxin contamination risk                  | Battilani Battilani, Paola, et alet al., 2016 |
| 13 | <i>Fusarium verticillioides</i><br>(Fumonisin producer)                | Maize                      | Drought predisposes ears to infection; warmer conditions raise fumonisin risk  | Munkvold, Gary P., Robert H. Proctor          |
| 14 | <i>Botryosphaeriaceae</i> spp. (Canker and dieback)                    | Grapevine, fruit trees     | Drought/heat stress predispose trees; climate stress drives outbreaks          | Desprez-Loustau et al., 2006,                 |
| 15 | <i>Ophiostoma novo-ulmi</i> (Dutch elm disease)                        | Elm trees                  | Spread facilitated by climate-driven vector (beetle) dynamics                  | Wainhouse, David, et al.(2016)                |



## Climate change and global warming in fungal plant diseases and emerging

Fungal plant pathogens are becoming a significant global threat as a result of climate change. Destructive fungi are expanding into new regions due to changing climates, and it accelerates their evolution, ecosystem, and food source. The expansion of including wheat rust and rice blast into unsuitable regions is facilitated by warming climates (Varma, Varun, and Daniel P. Bebbber. 2019). Food security risks in developing nations are elevated by emerging threats to wheat, maize, coffee, and bananas. Fones, Helen N., et al. (2020), and Priya, R. Sathya, et al., (2024) have observed that climate change has a dual effect on plant physiology, reduction in defence mechanisms under heat stress and an intensification of pathogen aggression. Fungal adaptation is enhanced by rapid environmental shifts and extreme weather and develops fungicide resistance (ceresini, Paulo Cezar, et al. 2018). Invasive fungi in forests such as *Phytophthora spp.* threaten ecosystem stability and biodiversity (Boyd, Ian, et al. 2013). Climate driven pathogen movement and increased global trade and travel have combined to create an unprecedented risk of fungal pandemics in plants (Binkley, Dan, and Richard F. Fisher, 2019). Current monitoring, breeding, and fungicide strategies may not be able to keep up with the rapidly evolving nature of fungal threats and highlight the need for integrated global strategies (Elad, Yigal, et al., 2015). The high-temperature nights and altered rainfall have been connected to epidemics of coffee leaf rust (*Hemileia vastatrix*) in Central America. (Avelino, Jacques, et al., 2015). According to Mehmood, Khalid, X. Qiu, and M. A. Khan (2025), heat and drought increase the frequency of Fusarium wilt symptoms in *solanaceous* crops, and nematode interactions show worse symptoms. The legacy effects of drought and heat make trees vulnerable to canker (Desprez-Loustau, Marie-Laure, et al., 2006). Impacts of wetter winters cause more severe *Phytophthora* root rots. Aflatoxin and fumonisin risks in maize and groundnuts are further increased by hot, dry seasons combined with humid storage (Battilani, Paola, et al., 2016). Fungal plant pathogens are fungi that infect and damage plants, resulting in diseases such as blights, wilts, rusts, and smuts. They frequently result in yield losses or plant death by disrupting photosynthesis, nutrient transport, and plant physiology. An emerging threat is a type of danger that is experiencing an increase in frequency, severity, or geographic distribution as a result of new ecological, environmental, or social factors. The main cause of the emergence of fungi is climate change, which also modifies the balance between hosts, and develop resistance to fungicides as a result of climate warming. The climate change-driven fungal emergence is a process in which the range, virulence, and impact of fungal plant pathogens are increased by altered climate regimes, with significant implications for agriculture and ecosystems (Fisher et al., 2012; Fones et al., 2020). Bebbber et al. (2013) demonstrated that crop pests and pathogens are shifting towards higher latitudes at a rate of



approximately 2.7 km per year, a trend that is strongly linked to global warming as a result of the poleward and altitudinal spread of fungi into previously unsuitable climates. Climate stress compromises plant defenses. Heat diminishes crop immunity, while drought and flooding can increase root exposure to soil-borne fungi. This creates conditions that stimulate pathogens like *Fusarium* to colonize more aggressively (Velasquez et al., 2018). Environmental change is rapidly adapted by fungal populations. The rapid evolution of virulence and fungicide resistance is driven by climate variability which selects for aggressive genotypes that can withstand fluctuating conditions (Fisher et al., 2020). Change in wind patterns facilitate long distance dispersal, while climate drivers precipitation patterns. The wheat rust spores (*Puccinia spp.*) can travel thousands of kilometers through wind and storms (Chakraborty and Newton, 2011). Pathogens spread across continents via global trade and travel, and warmer climates encourage invasive species to establish themselves in new habitats (Fisher et al., 2012). Pathogens spread across continents through global trade and travel, and warmer climates encourage invasive species to establish themselves in new environments (Fisher et al., 2012). Wheat rust (*Puccinia graminis f. sp. tritici, Ug99*) a highly virulent lineage is spreading from east Africa to Asia posing a threat to global wheat supplies due to improving climate conditions. The spread of rice blast (*Magnaporthe oryzae*) poses a threat to the health of rice. It is a staple food that is consumed by over 50% of the global population in the presence of climate induced humidity and flooding. The devastating coffee production issue identified as coffee leaf rust (*Hemileia vastatrix*) is associated with elevated nighttime temperatures and modified precipitation patterns in central America. Banana Panama diseases (*Fusarium oxysporum f. sp. cubense TR4*) endangers global banana supply chains by proliferating under monoculture stress and climatic fluctuations. *Phytophthora spp.* are accountable for forest dieback. The proliferation of invasive oomycetes and fungi adversely affects the biodiversity and carbon cycling in temperate and boreal forests (Boyd et al. 2013). Fungi are the primary cause of crop diseases worldwide, accounting for 10-16% of annual yield losses (Fones et al., 2020). The vulnerability of staple crops such as maize, rice, and wheat directly threatens global nutrition. Certain fungi like *Fusarium spp.*, produce mycotoxins that contaminate food supplies and pose health risks to humans and livestock. The ecosystem is at risk due to the emergence of fungal species that are driven by the climate, in addition to agriculture. The disruption of forests by tree pathogens results in the alteration of habitats and decline of species. Carbon sequestration capacity is diminished by tree mortality and it exacerbates climate change. Forests, grasslands, and wetlands are essential for the regulation of water and the fertility of the soil. The international nature of fungal spread renders it a biosecurity challenge. Pathogen adaptation heavily relies on management strategies, while surveillance remains fragmented. There are several recommendations



for risk mitigation. We recommend utilizing climate-based modeling and remote sensing to anticipate fungal outbreaks. The creation of crop varieties that demonstrate long-lasting resistance to a variety of fungal strains is another recommendation. The creation of crop varieties that demonstrate long-lasting resistance to a variety of fungal strains is another recommendation. Biological control, crop diversification, and agroecological practices to reduce the reliance on fungicides and also enhancing frameworks such as the International Plant Protection Convention to facilitate coordinated responses.

### **Climate Change, Fungal Plant Pathogens, and Adaptive Strategies**

There is a significant global transformation of ecosystems, agriculture, and plant-pathogen interactions as a result of climate change. Increased threats from fungal plant pathogens interactions as a result of climate change. Increased threats from fungal plant pathogens are among the most alarming consequences. These pathogens are already responsible for significant crop losses and forest decline. Risks is further exacerbated by the modification of temperature regimes, rainfall patterns, and atmospheric CO<sub>2</sub> levels as a result of climate change. Both pathogens and plants are implementing adaptive strategies that are biological and management-oriented, which are the determinants of future resilience. The adaptation of fungal pathogens to climate change, the response of plants and agricultural systems, and the appropriate adaptive strategies that researchers and farmers can implement to reduce risks. Long-standing destructive fungal plant pathogens include *Magnaporthe oryzae* (rice blast), *Fusarium oxysporum* (wilt fungi), and *Puccinia* (rust fungi). The climate change impacts are exacerbated in a variety of ways. The temperatures increase, fungi are able to disperse to higher latitudes and altitudes. The expansion of coffee leaf rust into the cooler highlands of Central America was contingent upon the rise in nighttime temperatures (Avelino et al., 2015). Bebbert et al. (2013) have observed pathogen reproduction rates can increase and infection seasons can be extended in warmer climates. Plants become more susceptible to fungicides, adaptive fungi develop resistance, particularly in monocultures (Hawkins, Nichola J., et al., 2019). Climate change fungal pathogens utilize a variety of adaptive mechanisms to improve their survival and dissemination. The ability of fungi to develop resistance against host defenses is facilitated by their rapid mutation rates and recombination. The *puccinia graminis Ug99* lineage was created to overcome wheat resistance genes (Singh, Ravi P., et al. 2011). Many fungi can change their growth rates, infection efficiency, and spore production based on temperature and humidity. Spores show plasticity under warm and humid conditions, producing more spores (Chakraborty and Newton, 2011). It is preferable to use strains that can withstand extreme temperatures. *Colletotrichum spp.* have greater heat tolerance, allowing them to colonize a broader range of hosts. Some fungi remain asymptomatic, conditions favor outbreaks, and it is



it is an important survival strategy in changing climates. Fungi can rapidly colonize new ecosystems through windborne spores, rain splash, and human-mediated transport. Climate-driven extreme weather makes long-distance spread easier. Plants and agricultural systems must also adapt to withstand fungal threats during climate change. Several adaptive strategies have emerged. Breeders are increasingly focusing on polygenic resistance (quantitative resistance) rather than single resistance genes that pathogens quickly overcome. Gene pyramiding or stacking multiple resistance genes shows slow fungal adaptation (Nelson, Rebecca, et al. 2018). CRISPR and genomic selection speed up the development of resistant varieties. Editing rice blast resistance genes to boost broad-spectrum immunity (Fones and Gurr, 2015). Crops benefit from changing planting or flowering times to avoid peak infection. In areas prone to wheat rust, farmers use climate-adjusted sowing dates. Endophytes and mycorrhizal fungi help plants withstand both abiotic and biotic stressors. Beneficial microbes can suppress pathogens and improve nutrient uptake under stress (Velasquez et al., 2018). Fungal spread and evolutionary potential are decreased by interconnecting crop rotation and landscape heterogeneity is essential to use plant biology and adaptive crop and forest management practices to reduce vulnerability. The biological control, genetic resistance, cultural traditions, and selective chemical use decreased dependency on fungicides and delay emergence of resistance. They incorporate controlling soil health, crop selection for climate and water efficient irrigation to reduce stress vulnerability. Early warning systems that integrate pathogen monitoring and climate models can forecast outbreaks and guide adaptive responses (Bebber et al., 2013). Adaptive strategies require international cooperation in outbreak control and resistance sharing. Changes in humidity provide an environment for frequent outbreaks of rice blast (*Magnaporthe oryzae*). Genomic tools are used in adaptive breeding programs to create resistant rice cultivars. The need for cooperative farmer strategies, resistant cultivars, and shade management was highlighted by the coffee leaf rust (*Hemileia vastatrix*) outbreak in Central America (Avelino et al., 2015). Fungi adapt faster than breeding efforts, as evidenced by wheat stem rust Ug99 pathogen overcomes resistance genes. Global monitoring networks and gene stacking strategies are examples of adaptive responses (Singh et al., 2011). The persistence of *Fusarium* in soils underscores the limitations of chemical control and is pushing researchers toward resistant banana varieties and agroecological diversification (Banana Panama Disease TR4, Ploetz, 2015). Future adaptive strategies must integrate ecological, technological, and sociopolitical approaches to forecast hotspots. Climate projections should be connected to models of fungal adaptation obtaining broad-spectrum resistance without compromising yield-boosting resilience by using biodiversity as opposed to monocultures.

## CONCLUSION



Climate change's modified precipitation, increased CO<sub>2</sub>, and more frequent extremes are some of the ways that it increases the threats posed by fungal plant diseases. These factors interact with host physiology, pathogen biology, and agroecosystems to change disease risks globally. Emerging threats include increased mycotoxin contamination, range expansions, forest diebacks, and drought-wilt complexes. Protecting crop productivity and food security requires adaptive measures like climate-smart agronomy, microbiome-informed management, resistance breeding, and predictive surveillance. Fungal plant pathogens and climate change are defined as emerging threats, which accurately reflects a rapidly changing crisis. Fungal range expansions, virulence, and host susceptibility are exacerbated by climate change. It changes the landscape of ecological and agricultural diseases. This threat transcends biology and poses a direct threat to ecological resilience, economic stability, and global food security. This necessitates immediate international cooperation, monitoring, and investment in resilient crops and the fusion of plant pathology and climate science. The example of a coevolutionary arms race is the interaction of fungal plant pathogens, climate change, and adaptation. Fungal pathogens are organisms that are able to quickly adapt to changes in the environment. The adoption of adaptive strategies by plants and human management systems is therefore necessary, ranging from agroecological diversification and climate-smart surveillance to resistance breeding and CRISPR-based solutions.

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