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Climate Change and Plant Diseases: How Emerging Conditions Reshape Plant-Pathogen Interactions / Review Article

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Abstract: Fluctuations in climate in the past few decades have had a dramatic effect on the relationship between plants and the pathogens that infect them at both the environmental and molecular levels. Global warming impacts a plant's defense system negatively by decreasing the immune chemicals manufactured within the plant, making it vulnerable to attack by disease. High humidity also affects the power of plants to close the spiracles in their leaves. The spiracles normally close to limit pathogen invasion, but under higher humidities, plants cannot effectively control these spiracles, and pathogenic fungi and bacteria are easier to enter through them. Increased atmospheric concentrations of carbon dioxide leads to changes in leaf morphology, for instance, through a reduction in spiracle density. This affects the ability of plants to resist specific pathogens. In the meantime, others such as powdery mildew take advantage of such changes to progress more rapidly. Climate change has caused some plant diseases to spread to new areas not originally infected by them, threatening agricultural production in these areas. Friendly microbes that live on plant roots and leaves are also pivotal in helping plants adjust to these climatic shifts and protect themselves from diseases. These microbes boost the immune power of plants and improve their resistance to drought and heat stress. In the future, the tendency is to use cutting-edge technologies such as genetic modification to enhance plant immunity, using artificial intelligence to predict disease outbreaks, and designing smart agricultural systems that provide farmers with early warnings and reduce reliance on chemical pesticides, making agriculture sustainable during climate change.

Keywords: Climate Change, Plant Immunity, Pathogen Interaction, Stomatal Regulation, Microbial Resistance

1- Introduction

The past few decades' climate change has been among the most pronounced environmental drivers that alter the plant pathogen interactions at both the molecular and environmental level. According to the Intergovernmental Panel for Climate Change (IPCC) report, after the pre-industrial era, the mean overall temperature increases by 1.1°C, with an additional increase of 1.5°C to 2°C. This elevated temperature interferes with the basic immune process of the plant in primary immunity (PTI) as well as induced immunity (ETI) and opens the door to certain pathogens more readily and efficiently (Chakraborty and Newton, 2011). Air humidity and precipitation play an effective role in the mechanism of the plant to regulate the opening and closing of its mouth. It is the first line of defense against disease-causing agents such as Pseudomonas syringae and Collotrichum spp. It has been demonstrated in recent studies that high relative humidity (>85%) impairs the stomas' ability to respond to pathogen signals via the ABA pathway, enabling the invasion of fungal ovals into the inner tissue of the plant (Zhang et al., 2022). Severe drought cycles, on the contrary, can initiate dry root accumulation and endosaline, break immunity and promote the spread of soil-borne diseases such as Fusarium oxysporum (Risteino et al., 2022). Meanwhile, the constant increase in carbon dioxide (CO_2) content affects the morphological leaf structure by decreasing the density of stomas and changing the structure of the wax layer on the surface of the sheet. This has the ability to reduce the body resistance barrier of aerobic pathogens such as Botrytis Cinérea (Bebber et al., 2013; Smith & Reynolds, 2023). However, some studies have uncovered the evolution of novel adaptation mechanisms in plants, such as increased production of blue radicals (AFCs) and the activation of the CBP60G gene, which are able to restore high-temperature transmission of signaling networks (Li et al., 2024).

At the same time, recent studies also revealed geographical changes in plant disease transmission models. Disease of wheat spreads from South America to South Asia and Africa, threatening seasonal temperatures and humidity increases, as well as agricultural productivity in the previously uncharacterized regions (Cruz et al., 2023). Root microbias are now understood to provide tolerance to harsh climate stress. Experiments have confirmed that certain strains of PGPR induce plants to synthesize antioxidant chemicals and develop resistance in media corresponding to heat or water stress (Kumar et al., 2022).

The purpose of this article is to present a detailed and accurate scientific diary of complex interactions between plants and pathogens on the basis of recent climate change, focusing on molecular mechanism alterations, physiological effects, and geographical changes in diseases.

1. Effect of temperature on plant immunity

Temperature is one of the climatic factors that most affect plant immune function and directly affects the effectiveness of natural and adaptive immunity (PTI) and dependent immunity (ETI), particularly the salicylic acid (SA). Several studies have shown that the effects of plants at high temperatures are often higher than 30°C, leading to a significant reduction in salicylic acid products. It is an important molecule in the regulation of immune protection against biosal pathogens such as Pseudomonas syringae, 2024).

This violation of Path SA is reflected in the efficacy of primary immune responses (PTIs) related to recognition of molecular models associated with pathogens (PAMPs), and depends on the effect (ETI), indirect activation of stable proteins (R-Belki) (Hua et al., 2022). It has been found that the expression of protective genes such as PR1 and PR5, as well as the accumulation of AFC (reactive oxygen form) decreases at high temperatures, increasing the susceptibility of plants to infection (Huot et al., 2017).

A recent development in this field was a study published in Wired (2023) and has since been recorded in Springer, showing that activation of the CBP60G gene can rearrange immune protection responses at high temperatures. CBP60G functions as a transcriptional regulator and helps maintain normal expression of the gene at high temperatures, increasing the balance of plant defense. It has been observed that Arabidopsis plants genetically modified to improve CBP60G expression can restore effective resistance to bacterial infections at temperatures above 32°C (Kim et al., 2023). Furthermore, certain studies have shown that the effect of temperature is not limited to molecular effects, but is applied to alterations in the rate of photosynthesis and inhibition of the expression of specific sensory receptors, such as FLS2.

2 Humidity and Balance: Hormonal Signal Transmission

The relative humidity of the environment plays an important role in determining the success or failure of plant pathogens penetrating the physical barrier of the plant the most notable of these barriers representing the initial point of contact between the external environment and the plant's inner fabric. Under normal conditions, plants close their stomachs when determining the presence of pathogens through pathways including PAMP, MAPK, and ROS to prevent pathogen penetration (Melotto et al., 2008).

However, at high humidity conditions (>85%), this response weakens, and plants cannot effectively close the stomach, allowing pathogens to introduce and initiate infections (Zhang et al., 2022). Recent studies have shown that several pathogens, such as Pseudomonas syringae, process the pathway of Abuchesate hormone (ABA) by secretly secrecy of secret effective proteins that open up stomata again even after being closed by plant defense signals (Jiang et al., 2021).

Ironically, some pathogens use the ability to close the mouth of plants! For example, *Colletrichum spp*. In fungal infections such as, mouth closures maintain leaf leaves humidity, improve internal humidity, and create ideal conditions for conflict growth and progression of infection (Ristaino et al., 2022). Conversely, plants have developed intelligent mechanisms for the retention of USTIK disclosures in high humidity conditions, including the use of SA and inefficient signaling means to inhibit mouth reopening in a synchronous manner that maintains ABA signaling and water balance and protection (Prodhan et al., 2020). A study published in Frontiers in Plant Science (2023) shows that Ustil is not only a physical hole, but also a "dynamic sensor" that controls the balance between defense and gas exchange, especially in wet environments.

3. Increase in carbon dioxide (CO_2) and structural changes in plants

Atmospheric CO_2 levels are one of the major forces behind global climate change between about 280 games (ppm) per 280 games and 420 hours/million in 2023 (IPCC, 2023). The increase causes deep structural and physiological changes in plants that affect growth, morphology, and disease response. In recent studies, it has been demonstrated that CO_2 increase leads to a decrease in stomatal density on the leaf surface as an adaptation to enhance water utilization efficiency by reducing evaporation loss (Gray et al., 2000; Xu et al., 2021). Decreasing stoma density can reduce the activity of aerobic pathogens, but it might be combined with other unwanted responses, e.g., increased trichomes and reduced protective wax layers.

Furthermore, studies have shown that high $CO2$ is converted into plant primary and secondary metabolism, e.g., phenolic science, which reduces protective capacities against certain fungal pathogens and reduced levels of secondary protection compounds like alkaloids (Pangga et al., 2011). Also, vice versa, certain pathogens, particularly those on the basis of rapid growth of carbon-rich conditions, may take advantage of such an environment, such as Fusarium species, and increase infection severity. (Eastburn et al., 2010). It should be noted that some studies have been done which indicate that high CO_2 retards the elongation of some long pathogens, such as plant spheres infestans, through plant physiology indirect effects and delayed leaf maturity (Chakraborty and Datta, 2003). However, the effect is not always positive. The reason is that it could be correlated with an incomplete breakdown of resistance processes to make plants susceptible to other pathogens.

4. Geographical distribution of plant diseases

The impact of climate change Climate change has now become the term used to describe geographical distribution and distribution of many plant diseases. With increased temperatures and increasing levels of moisture and dry seasons, the diseases have begun to manifest, extending to areas previously unoccupied, representing a serious threat to world food security include :

4.1. Fungal Disease: *Aspergillus* as an example The *Aspergillus* genus, particularly Aspergillus flavus, is one of the most dangerous mushrooms produced by aflatoxins. Statistics published in Times (2023) show that temperatures above 30°C and high relative humidity in regions such as East Africa and the Indian subcontinent are among factors contributing to increased spread of the fungus during development of corn and peanuts. The harmful effect of this fungal fungus is not limited to agriculture alone, but also extends to public health, especially since it is the main causative agent of aspergillosis in immunocompromised individuals (Battilani et al., 2016).

4.2. Wheat explosion appearance: One of the most tangible examples of the effect of climate change is the cases that affect disease transmission. The illness first happened in South America in the 1990s, but was discovered to have happened lately in Bangladesh in 2016 and in Zambia in 2018 due to climatic conditions alterations and new traveling tours (Islam et al., 2020). The disease is highly destructive and results in 100% loss of infected parts, and the epidemic is associated with recurrent heat waves, fog, and over 85% humidity (Inou et al., 2021; Cruz et al., 2023).

4.3. Seasonal changes and regional model changes: In Europe, disease microbes gradually disappear from the traditional range of reduced winter cooling for the deterioration of peace to some bacteria conflicts or stages, but new diseases arise in northern climates previously too cold to support pathogen activity (West et al., 2021). For example, the transmission of FOMA stem ulcers in British canolal cultures transmitted to other regions at low north temperatures during winter freezes (Evans et al., 2019).

4.4 Microbial plants as a secondary immunity: A silent partnership in climate stress resistance plant microbes, like various microbial plant communities, have several microbial plant-related communities and sheets but invisible yet essential lines of defense against disease, especially in light of increasingly fluctuating climates. Previous studies have proven that changes in temperature, humidity, and carbon dioxide levels directly affect the composition and balance of rhizosphere microbiome and potentially threaten plant immunity and, conversely, can induce compensatory defense mechanisms (Sumpi et al., 2021). Plants change the composition of their plant microbiota when they are under water deficit or heat stress conditions to excrete a variety of organic compounds (root excretion) to draw particular microorganisms that are efficient in inducing systemic resistance (ISR) (De Vries et al., 2020). For example, rhizosphere bacterial plant development (PGPRs), such as subspecies and Pseudomonas, fluoroscopy shows potential for increased stability of the fungal pathogen plants such as Fusarium even in hot temperatures and extreme droughts (Lareen etal. 2016).

Symbiotic fungi such as mycorrhizal not only improve the absorption of mineral elements such as phosphorus but also improve plant stability by inducing physiological and genetic responses including two important pathways: jasmonic acid (JA) and salicylic acid (SA) and plant defensive systems (Wang et al. Moreover, microorganisms in the phylosphere also acquire additional value, and studies find that some of the sphingomonas and methylobacteria species rectify the micro-selfishness of leaf leaves, suppressing the growth of aerobic microorganisms such as Xanthomonas. (Berg et al., 2020). There have been calls in recent years for the development of "plant-based probiotics" - microbial blends formulated to activate immunity and disease resistance that are directly sprayed on crops as alternative or preferred means to chemical pesticides, particularly under the ordinary conditions induced by climate (Company et al., 2019).

4.6 Future tools and strategies for preventing plant disease during climate change: To reverse the increasing threat of plant diseases fueled by global warming, there is a need for genetic, technical and analytical capacity to create stable adaptive agricultural systems. In recent times, eyewitnesses have become a key innovation in multi-layer prevention policies as a result of advances in plant genetics and artificial intelligence applications.

Stability and immunoregulatory genes in seeds

One of the most notable recent trends has been the development of hyper productive varieties in plants by the incorporation of climate- and pathogen-resistant genes, such as the CBP60G gene, and has proved to be effective in enhancing immunoacids (SA). Along with traditional genetic modifications, applications of precise gene editions such as CRISPR/CAS9 are developing rapidly, allowing specific sites in the genome to be changed to improve the production of immune receptors (R-genes) or to remove genes that destabilize them (Zhang et al., 2022). Immunostimulant chemicals have also been designed, known as plant-based immune dealers (PIAs) agents, and can be sprayed to induce defensive reactions without introducing new genes.

Digital modeling and artificial intelligence in prevention and prediction:
Considering the dynamics of pathogen transmission, traditional surveillance is insufficient in view of climate control. Hence, scientists turn to the use of mathematical models such as neuronal differential equations (neuron OD) and predict the emergence of diseases such as black banana tobacco and wheat rust from environmental and pathogenic genomic data (Martínez-Salvador and AL). Studies in Arxiv and African Journals Online (AJOL) show that such models are extremely powerful in prognosis even without big data and are extremely suitable for developing countries. Enhance digital systems in developing countries today this appeal is obvious to invest in agricultural digital infrastructure, using networks with intelligent field sensors, mobile and real-time environmental analysis devices for farmers to provide early warning systems and reduce their reliance on pesticides (FAO, 2022).

2- Conclusions and Recommendations

1- Climate change impacts the plant disease system in a multifaceted way through multiple drivers of the environment such as temperature, humidity, and carbon dioxide, as well as structural elements such as leaf apertures and composition of plant microbiome.
2- Plants exhibit considerable heterogeneity in immune response depending upon the type of pathogen and climatic factor, reducing the effectiveness of traditional means of resistance.
3- Beneficial microbes that are plant leaf and root-associated are of prime importance in facilitating plant tolerance and plant immunity against unpredictable climatic variability.
4- Climate change is leading to the spread of plant diseases to new regions, with negative implications for agricultural production within these regions and necessitating constant monitoring and interactive investigation of climatic disease.
5- Technologies such as genetic engineering (e.g., gene editing) and artificial intelligence are recasting the future of plant disease management by enhancing plant immunity and accelerating early warning of epidemic breaks.
6- Combining climate observation programs with environmental and biological information to assess epidemic risks and implement scientific preventive measures that mitigate the impact of climate change on plants is of utmost priority.

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