

Impact of climate change on the epidemiology of plant diseases

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Abstract

Climate change is increasingly recognized as a major driver of plant disease dynamics worldwide, altering environmental conditions that govern host–pathogen–environment interactions. This study aimed to synthesize current scientific evidence on the impacts of climate change on the epidemiology of plant diseases through an integrative literature review. A systematic search was conducted between March and April 2026 using the Web of Science, Scopus, SciELO, PubMed/MEDLINE, and CAPES Journal Portal databases. Peer-reviewed articles published between 2016 and 2026 in English or Portuguese were screened according to predefined inclusion and exclusion criteria, resulting in the selection of 17 studies for qualitative analysis. The findings demonstrated that climatic factors, particularly temperature, atmospheric CO₂ concentration, relative humidity, precipitation patterns, and leaf wetness duration, significantly influence pathogen survival, reproduction, dispersal, infection efficiency, and disease severity. Temperature emerged as the most influential variable; however, its effects varied substantially among pathosystems, reflecting differences in pathogen biology and host responses. The reviewed studies also indicated that climate change is facilitating the emergence and geographic expansion of plant pathogens into previously unsuitable regions, thereby increasing phytosanitary risks for economically important crops. Furthermore, altered climatic conditions may compromise the effectiveness of conventional disease management strategies, highlighting the need for adaptive approaches. The evidence underscores the importance of integrating epidemiological surveillance, predictive modeling, climate-informed risk assessment, host resistance breeding, and integrated disease management into agricultural adaptation frameworks. Future research should prioritize multidisciplinary approaches to improve the prediction and mitigation of climate-driven disease outbreaks under diverse agroecological conditions.

Keywords: climate change, plant disease epidemiology, host–pathogen interactions, emerging plant pathogens, disease forecasting.

Impacto das mudanças climáticas na epidemiologia de doenças de plantas

Resumo

As mudanças climáticas são cada vez mais reconhecidas como um dos principais fatores que influenciam a dinâmica das doenças de plantas em escala global, ao alterarem as condições ambientais que regulam as interações entre hospedeiro, patógeno e ambiente. Este estudo teve como objetivo sintetizar as evidências científicas atuais sobre os impactos das mudanças climáticas na epidemiologia das doenças de plantas por meio de uma revisão integrativa da literatura. Uma busca sistemática foi realizada entre março e abril de 2026 nas bases de dados Web of Science, Scopus, SciELO, PubMed/MEDLINE e Portal de Periódicos CAPES. Artigos revisados por pares, publicados entre 2016 e 2026, nos idiomas inglês e português, foram selecionados de acordo com critérios previamente estabelecidos de inclusão e exclusão, resultando na seleção de 17 estudos para análise qualitativa. Os

resultados demonstraram que fatores climáticos, especialmente temperatura, concentração atmosférica de CO₂, umidade relativa do ar, regime de precipitação e duração do molhamento foliar, influenciam significativamente a sobrevivência, reprodução, dispersão, eficiência de infecção e severidade dos patógenos. A temperatura destacou-se como a variável mais influente; entretanto, seus efeitos variaram substancialmente entre os diferentes patossistemas, refletindo diferenças na biologia dos patógenos e nas respostas dos hospedeiros. Os estudos revisados também indicaram que as mudanças climáticas estão favorecendo a emergência e a expansão geográfica de patógenos vegetais para regiões anteriormente consideradas inadequadas, aumentando os riscos fitossanitários para culturas de importância econômica. Além disso, as alterações climáticas podem comprometer a eficácia das estratégias convencionais de manejo de doenças, evidenciando a necessidade de abordagens adaptativas. As evidências ressaltam a importância da integração entre vigilância epidemiológica, modelagem preditiva, avaliação de riscos baseada em variáveis climáticas, melhoramento genético para resistência e manejo integrado de doenças nos programas de adaptação agrícola. Pesquisas futuras devem priorizar abordagens multidisciplinares capazes de aprimorar a previsão e a mitigação de surtos de doenças induzidos pelas mudanças climáticas em diferentes condições agroecológicas.

Palavras-chave: mudanças climáticas, epidemiologia de doenças de plantas, interações hospedeiro-patógeno, patógenos emergentes de plantas, previsão de doenças, manejo integrado de doenças

1. Introduction

Climate change has emerged as one of the most pressing global challenges of the twenty-first century, exerting profound effects on natural and agricultural ecosystems. Since the Industrial Revolution, atmospheric carbon dioxide (CO₂) concentrations have exceeded 420 ppm, while global mean temperatures have increased by approximately 1.1 °C relative to pre-industrial levels (Rezaei et al., 2023; Rising et al., 2022; Singh et al., 2023; Verma et al., 2025). These climatic alterations are accompanied by shifts in precipitation regimes, increased frequency of extreme weather events, prolonged droughts, and changes in seasonal patterns, all of which directly affect agricultural productivity and food security worldwide (Bibi; Rahman, 2023; van Leeuwen et al., 2024).

According to projections from the Intergovernmental Panel on Climate Change (IPCC), global temperatures may rise between 2.5 and 4.0 °C by the end of the century under high-emission scenarios. Such changes are expected to substantially modify ecological interactions and biological processes, including those governing the occurrence and spread of plant diseases (Singh et al., 2023). Plant pathogens, including fungi, bacteria, viruses, and nematodes, are responsible for significant yield losses in major crops, causing annual reductions estimated between 20% and 40% of global agricultural production and generating economic losses exceeding US\$ 220 billion (Saroeung et al., 2026; Sarun, 2026).

The impact of climate change on plant health extends beyond increased disease incidence. Climatic variables directly influence the epidemiological processes that determine pathogen survival, reproduction, dispersal, infection efficiency, and host susceptibility. These effects can be understood through the classical plant disease triangle, which establishes that disease development depends on the interaction among a susceptible host, a virulent pathogen, and a favorable environment (Garrett et al., 2011). Climate change simultaneously affects all three components of this framework, thereby altering disease dynamics at multiple biological and spatial scales (Hossain et al., 2024; Singh et al., 2023).

Temperature increases may accelerate pathogen life cycles, shorten latent periods, and increase the number of infection cycles during a growing season (Elad; Pertot, 2014). Changes in rainfall patterns and relative humidity can enhance inoculum production, dispersal, and infection success, while elevated atmospheric CO₂ concentrations may modify plant physiology, canopy architecture, and defense mechanisms. Consequently, environmental conditions increasingly act as drivers of plant disease epidemics rather than merely background factors (Garrett et al., 2011; Elad; Pertot, 2014).

One of the most widely documented consequences of climate change is the geographical redistribution of plant pathogens and pests. Between 1960 and 2013, disease-causing organisms expanded their distribution by an average of 2.7 km per year toward the poles and 6.1 m per year in elevation, enabling colonization of regions previously unsuitable for their establishment (Bebber et al., 2013; Fortuna et al., 2022). This process promotes the emergence of novel host-pathogen interactions in areas where cultivated plant populations have not co-evolved with these organisms, increasing vulnerability to disease outbreaks and challenging existing management strategies (Bebber; Gurr, 2015).

In Brazil, the implications of these changes are particularly relevant due to the country's prominent role in global

agricultural production. Major crops such as soybean, maize, coffee, sugarcane, and citrus are cultivated across tropical and subtropical regions that are highly sensitive to climatic variability (Ghini et al., 2011). A comprehensive assessment of 304 Brazilian pathosystems conducted by Angelotti et al. (2024) indicated that nearly half of the analyzed diseases may become more severe under future climate scenarios. Important diseases such as Asian soybean rust (*Phakopsora pachyrhizi*) and black Sigatoka of banana (*Mycosphaerella fijiensis*) already exhibit epidemiological patterns associated with regional climatic changes, highlighting the growing phytosanitary risks for Brazilian agriculture.

Despite increasing scientific attention to this topic, important knowledge gaps remain regarding the integration of climate change impacts across different pathosystems, climatic variables, and management approaches. Existing studies often focus on specific crops or pathogens, limiting a broader understanding of global epidemiological trends and their implications for disease management and agricultural adaptation. Furthermore, comprehensive reviews that connect international evidence with the realities of tropical agricultural systems, particularly those of Brazil, remain scarce (Chakraborty; Newton, 2011; Ghini et al., 2011).

Given the rapid expansion of scientific literature in this field, synthesizing current evidence has become essential to support researchers, extension agents, crop consultants, and policymakers in developing effective adaptation strategies. Such efforts are also aligned with international climate commitments established under the Paris Agreement and with recent discussions on agricultural resilience and food security promoted during COP30, held in Belém, Brazil, in 2025 (Brasil, 2025).

Therefore, this study aimed to conduct an integrative literature review on the impacts of climate change on the epidemiology of plant diseases, focusing on the effects of climatic variables on the plant disease triangle, the geographic redistribution of emerging pathogens, and the implications for phytosanitary management and agricultural adaptation.

2. Material and Methods

2.1 Study design

This study was conducted as an integrative literature review, a methodological approach that enables the synthesis and critical analysis of scientific evidence derived from studies employing different methodological designs (Whittemore & Knafl, 2005). The review followed the six methodological stages proposed by Souza et al. (2010): (i) formulation of the research question; (ii) literature search; (iii) data extraction; (iv) critical appraisal of the included studies; (v) synthesis and discussion of findings; and (vi) presentation of results.

The guiding research question was: How do climate change-related variables influence the epidemiology of plant diseases, particularly regarding pathogen occurrence, distribution, severity, and host–pathogen–environment interactions?

2.2 Information sources and search strategy

The bibliographic search was performed between March and April 2026 in the following electronic databases: Web of Science, Scopus, Scientific Electronic Library Online (SciELO), PubMed/MEDLINE, and the CAPES Journal Portal. Search terms were selected from controlled vocabularies, including Medical Subject Headings (MeSH) and Descritores em Ciências da Saúde (DeCS), complemented by free-text keywords associated with plant pathology and climate change. The main search strategy employed was: ("climate change" OR "global warming") AND ("plant disease" OR "plant pathology") AND ("epidemiology" OR "disease incidence"). Equivalent terms in Portuguese were also used when applicable. Search strategies were adapted according to the indexing structure and search syntax of each database.

2.3 Eligibility criteria

Studies were considered eligible when they met the following criteria:

- Published between January 2016 and April 2026;
- Written in English or Portuguese;
- Available in full text;
- Original research articles or review articles;
- Addressed the effects of climatic variables on plant disease epidemiology, pathogen distribution, disease

severity, host susceptibility, or phytosanitary risks.

The following documents were excluded:

- Conference abstracts;
- Editorials, letters, and opinion papers;
- Theses, dissertations, monographs, and undergraduate final projects;
- Duplicate records;
- Studies unrelated to agricultural or cultivated plant diseases.

2.4 Study selection

The study selection process followed the recommendations of the PRISMA 2020 Statement (Page et al., 2021). A total of 111 records were initially identified across all database searches. After the removal of 54 duplicate records, 57 studies remained for title and abstract screening. Subsequently, 20 records were excluded for failing to meet the eligibility criteria. The remaining 37 articles underwent full-text assessment, resulting in the exclusion of 20 studies due to insufficient focus on climate-related epidemiological impacts or lack of relevant outcome data. Consequently, 17 studies met all inclusion criteria and were included in the final qualitative synthesis.

Duplicate records were identified using reference management software and subsequently confirmed through manual inspection. Duplicate articles indexed in more than one database were removed before the screening process. Two independent reviewers performed title, abstract, and full-text screening. Any disagreements regarding study eligibility were resolved through discussion until consensus was achieved. When consensus could not be reached, a third reviewer made the final decision. The complete study selection process is illustrated in the PRISMA 2020 flow diagram (Figure 1).

2.5 Data extraction

Data extraction was conducted using a standardized spreadsheet developed specifically for this review. The following information was collected from each study:

- Authors and year of publication;
- Country or region of study;
- Study design;
- Crop species;
- Pathogen or disease investigated;
- Climatic variable evaluated;
- Main epidemiological outcomes;
- Principal conclusions.

Data extraction was independently performed by two reviewers using a standardized spreadsheet. After completion, the extracted information was compared, and inconsistencies were resolved through discussion and verification of the original publications.

2.6 Data analysis and synthesis

The included studies were analyzed using a qualitative descriptive approach. Findings were grouped into thematic categories according to the primary climatic drivers investigated, including temperature, atmospheric CO₂ concentration, precipitation patterns, relative humidity, and leaf wetness duration. The synthesis focused on identifying common epidemiological trends, pathogen responses to climate variability, geographic shifts in disease distribution, and implications for disease management and agricultural adaptation strategies. Particular attention was given to the effects of climate change on the components of the plant disease triangle, namely host susceptibility, pathogen development, and environmental favorability.

2.7 Methodological quality assessment

The methodological quality of the included studies was independently assessed by two reviewers considering study objectives, experimental design, sample characteristics, climatic variables investigated, analytical methods, and

consistency of conclusions. Disagreements were resolved through consensus. Because the review included heterogeneous study designs, no numerical quality scoring system was applied.

3. Research Summary

3.1 Study selection

The literature search initially identified 111 records across the databases consulted. After the removal of 54 duplicate records, 57 articles underwent title and abstract screening. Of these, 20 studies were excluded because they did not meet the eligibility criteria, leaving 37 articles selected for full-text assessment. During the full-text evaluation stage, 20 studies were excluded because they had an insufficient focus on climate-associated epidemiological impacts. At the end of the process, 17 studies fully met the inclusion criteria and were retained for the qualitative synthesis.

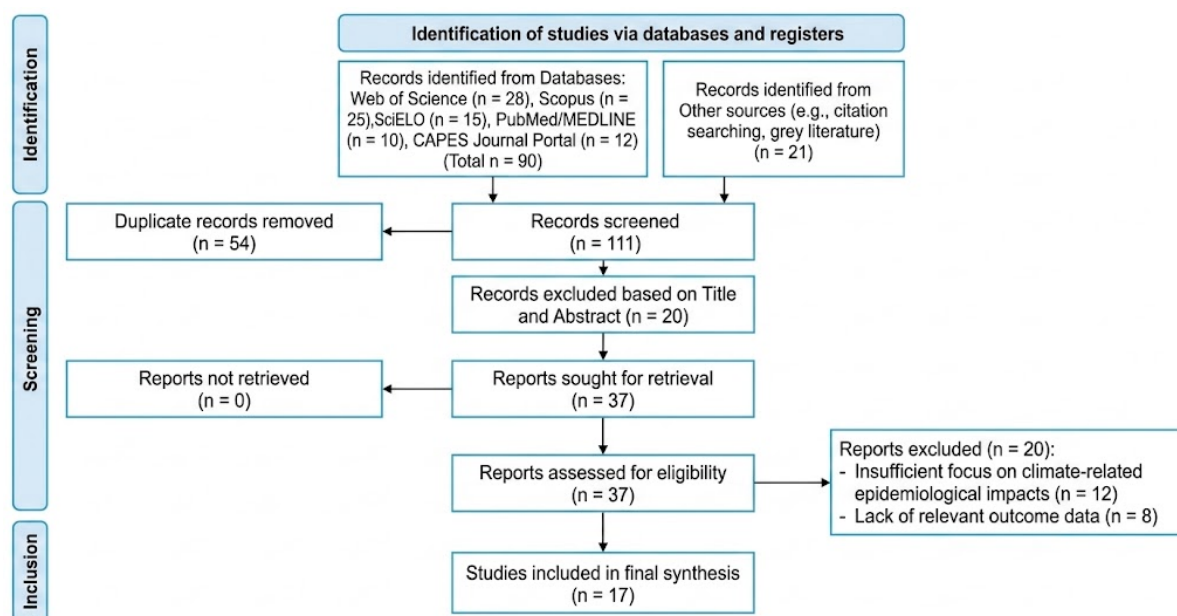


Figure 1. PRISMA 2020 flow diagram illustrating the study selection process. Source: Authors, 2026.

3.2 General characteristics of the included studies

The selected studies were published between 2016 and 2026 and comprised experimental studies, epidemiological investigations, predictive modeling studies, occurrence surveys, scenario analyses, and literature reviews. Wheat was the most frequently investigated crop, followed by potato, maize, coffee, and canola. Several studies also addressed broader plant–pathogen interactions under changing environmental conditions.

The pathogens evaluated included fungal, bacterial, and viral agents of major agricultural importance, such as *Phytophthora infestans*, *Blumeria graminis* f. sp. *tritici*, *Fusarium graminearum*, *Leptosphaeria maculans*, *Hemileia vastatrix*, *Dickeya zaeae*, *Puccinia striiformis*, *Puccinia polysora*, *Puccinia sorghi*, and BYDV-PAV. Temperature, atmospheric CO₂ concentration, relative humidity, precipitation, leaf wetness duration, and climatic seasonality were the most frequently investigated environmental variables.

3.3 Effects of climatic variables on plant disease epidemiology

Temperature emerged as the most influential climatic factor affecting plant disease epidemiology. Most studies reported that increasing temperatures altered pathogen development, reproduction, adaptation, dispersal, and disease severity. Evidence from *Phytophthora infestans* demonstrated significant thermal adaptation capacity, suggesting that some pathogens may rapidly respond to changing climatic conditions and expand their geographical distribution.

Elevated atmospheric CO₂ was frequently associated with changes in host–pathogen interactions. Studies

involving wheat, canola, and virus-vector systems showed that increased CO₂ concentrations can modify plant physiology, disease severity, pathogen colonization, and vector performance. However, the magnitude and direction of these effects varied among pathosystems, indicating that elevated CO₂ does not exert a uniform influence across crops and pathogens.

Relative humidity, precipitation, and leaf wetness duration were consistently identified as critical drivers of infection processes. These variables directly affected spore germination, inoculum production, pathogen survival, and disease dissemination. In coffee production systems, for example, disease risk models indicated that variations in canopy temperature and leaf wetness substantially altered the potential occurrence of coffee leaf rust.

Several studies also highlighted the importance of climatic seasonality and future climate scenarios. Modeling approaches predicted shifts in the distribution of economically important pathogens, including *D. zea* and rust-causing fungi, suggesting increased phytosanitary risks in regions that are currently considered climatically unsuitable for disease establishment.

3.4 Responses of major pathosystems to climate change

The wheat pathosystem was the most extensively investigated among the selected studies. Research involving powdery mildew, stripe rust, Fusarium head blight, seedborne fungi, and barley yellow dwarf virus consistently indicated that climate change may increase disease pressure through alterations in temperature, humidity, and atmospheric CO₂ concentrations.

These changes may compromise crop productivity and challenge current management strategies. Studies conducted with potato demonstrated that *P. infestans* possesses considerable adaptive potential to thermal variation, highlighting the possibility of accelerated pathogen evolution under future climatic conditions. Similarly, maize-related studies predicted expansion of bacterial stalk rot and rust diseases under projected climate scenarios.

In coffee, disease forecasting models suggested that changes in temperature and leaf wetness duration may alter the epidemiological dynamics of coffee leaf rust. For canola, elevated CO₂ influenced disease development caused by *L. maculans*, although pathogen responses differed according to host resistance mechanisms and environmental conditions. Broad-scale reviews further demonstrated that climate change affects not only pathogen populations but also plant immunity, host resistance mechanisms, and the effectiveness of conventional disease management practices. Collectively, the studies indicate that climate-driven changes are likely to reshape host–pathogen interactions, increase disease emergence risks, and create new challenges for global agricultural production systems.

3.5 Summary of included studies

Table 1 presents the studies included in the review.

Table 1. Characteristics of the studies included in the review.

Author and year	Study design	Crop or host	Pathogen, disease, or interaction investigated	Climatic or environmental variable
Bebber et al. (2016)	Climate modeling	Coffee	Coffee leaf rust	Canopy temperature and leaf wetness duration
Savary et al. (2017)	Scenario analysis	Wheat	Global wheat health	Climate and phytosanitary scenarios
Matić et al. (2018)	Experimental	Wheat	Wheat powdery mildew caused by <i>Blumeria graminis</i> f. sp. <i>tritici</i>	CO ₂ and temperature
Hernandez & Martinez (2018)	Review	Plants, animals, and humans	Fungi associated with environmental disturbances	Environmental changes and climatic events

Author and year	Study design	Crop or host	Pathogen, disease, or interaction investigated	Climatic or environmental variable
Zou et al. (2019)	Experimental	Canola	<i>Leptosphaeria maculans</i>	Elevated CO ₂
Timmusk et al. (2019)	Experimental	Wheat	<i>Fusarium graminearum</i>	Biocontrol under climate risk conditions
Wu et al. (2020)	Experimental and evolutionary	Potato	<i>Phytophthora infestans</i>	Temperature
Moreno-Delafuente et al. (2020)	Experimental	Wheat	BYDV-PAV, wheat, and aphid vector	CO ₂ and temperature
Shabana et al. (2021)	Observational and correlational	Wheat	Pathogenic and toxigenic seedborne fungi	Temperature, humidity, precipitation, wind, and solar radiation
Cohen et al. (2022)	Review and occurrence study	Various crops	<i>Macrophomina phaseolina</i>	Elevated temperature and aridity
Shen et al. (2022)	Experimental and population genetic	Potato	<i>Phytophthora infestans</i>	Temperature
Son & Park (2022)	Review	Agricultural crops	Plant immunity mechanisms	Temperature, humidity, and CO ₂
Singh et al. (2023)	Review	Agricultural crops and natural ecosystems	Plant pathogens	Climate, distribution, incidence, and severity
Shahid et al. (2024)	Potential distribution modeling	Maize	<i>Dickeya zeae</i>	Temperature and precipitation
Silva et al. (2024)	Review	Cultivated plants	Plant breeding and climate adaptation	Climate change
Lee et al. (2025)	Epidemiological study	Maize	<i>Puccinia polysora</i> and <i>Puccinia sorghi</i>	Occurrence, prevalence, and distribution
Aslam et al. (2026)	Review	Wheat	Stripe rust caused by <i>Puccinia striiformis</i> f. sp. <i>tritici</i>	Temperature, precipitation, humidity, and climate variability

Source: Authors, 2026.

4. Epidemiological Synthesis and Discussion

4.1 Climate change and the reconfiguration of the plant disease triangle

The studies included in this review consistently indicate that climate change influences plant disease epidemiology (Figure 2) by simultaneously affecting the three components of the plant disease triangle: the host, the pathogen, and the environment. This finding reinforces the conceptual framework proposed by Garrett et al. (2011), which recognizes disease development as the result of dynamic interactions among these components rather than the isolated action of a pathogen. Consequently, climate change should not be viewed merely as an external environmental driver but as a factor capable of reshaping the entire epidemiological system.

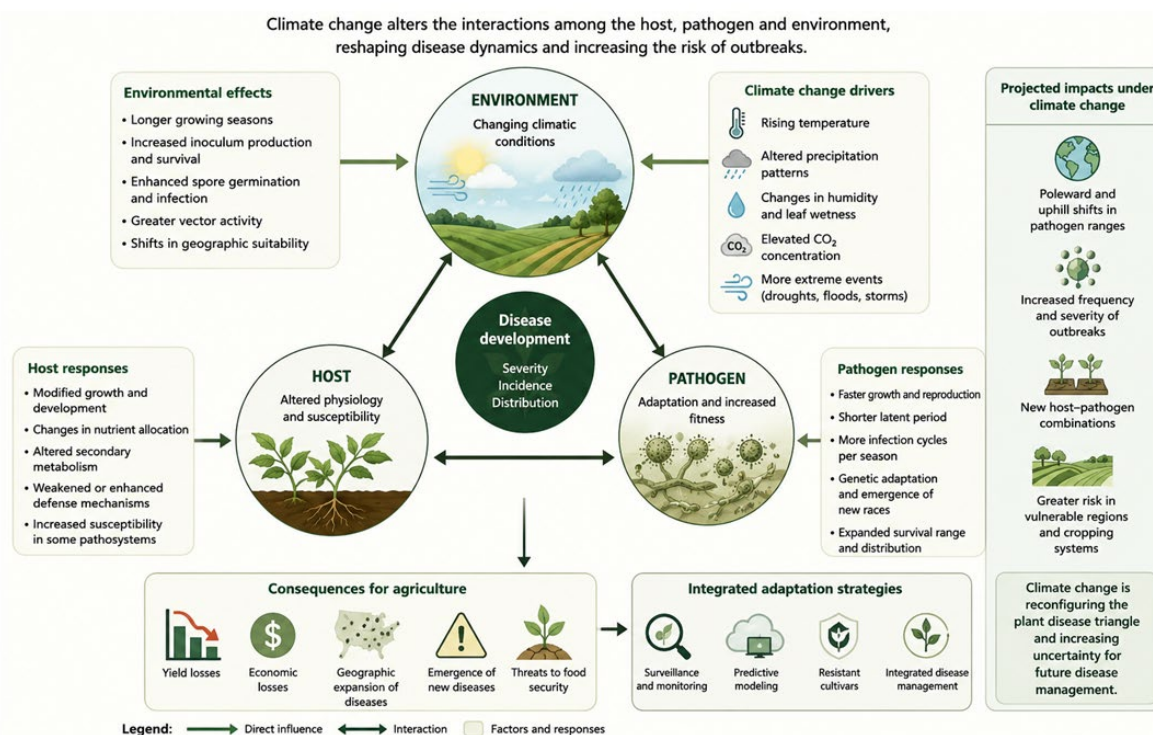


Figure 2. Climate change and the reconfiguration of the plant disease triangle. The figure illustrates how climate change reshapes plant disease epidemiology by simultaneously affecting the three components of the disease triangle: environment, host, and pathogen. Rising temperatures, altered precipitation patterns, changes in humidity and leaf wetness duration, increased atmospheric CO₂ concentrations, and a greater frequency of extreme weather events modify environmental conditions that favor disease development. These changes influence plant physiology and defense mechanisms, as well as pathogen survival, adaptation, reproduction, dispersal, and aggressiveness. As a consequence, shifts in disease incidence, severity, and geographic distribution are observed, promoting the emergence of new pathosystems and the expansion of pathogens into previously unsuitable regions. The figure also highlights potential impacts on agriculture, including yield losses, economic damage, increased threats to food security, and the emergence of new diseases, while presenting adaptation strategies such as epidemiological surveillance, predictive modeling, resistant cultivar development, and integrated disease management. The interaction among these factors demonstrates that climate change acts as a major driver of transformation in plant disease systems and future phytosanitary risks. AI source and verified by the authors, 2026.

At the pathogen level, several studies demonstrated that climatic variables directly influence survival, reproduction, adaptation, and dispersal processes. Singh et al. (2023) reported that increasing temperatures and changing precipitation regimes can modify pathogen biogeography, disease incidence, and epidemic intensity, thereby increasing phytosanitary risks for agricultural production systems. Experimental studies involving *Phytophthora infestans* provide compelling evidence of these processes.

Shen et al. (2022) demonstrated that mitochondrial genomic variation is associated with thermal adaptation, suggesting that local climatic conditions may exert selective pressure on pathogen populations. Similarly, Wu et al. (2020) showed that thermal acclimation can rapidly alter pathogen fitness and adaptive capacity, highlighting the evolutionary potential of plant pathogens under changing climatic conditions.

Climate change also affects host responses. Son and Park (2022) emphasized that elevated temperature, atmospheric CO₂ concentration, and changes in humidity can alter plant immune responses, potentially compromising resistance mechanisms that evolved under historical climatic conditions. This interpretation is supported by Zou et al. (2019), who observed that disease severity in the *Brassica napus*–*L. maculans* pathosystem varied according to atmospheric CO₂ concentration and the specific host–pathogen interaction involved. These findings suggest that future disease outcomes will depend not only on pathogen adaptation but also on the capacity

of plants to maintain effective defense responses under altered environmental conditions.

The environmental component of the disease triangle appears to function as the primary mediator of these interactions. Variations in temperature, humidity, precipitation, and leaf wetness duration influence pathogen infection efficiency, inoculum production, dispersal, and host susceptibility. Consequently, climatic conditions increasingly act as active drivers of epidemics rather than passive background factors. This interpretation aligns with previous theoretical frameworks that predict climate-mediated shifts in disease dynamics across multiple agricultural systems.

Despite the overall convergence among studies, important differences were observed regarding the direction and magnitude of climatic effects. While Singh et al. (2023) highlighted a general tendency toward increased disease risks and pathogen expansion under future climate scenarios, Matić et al. (2018) reported that elevated temperatures reduced the development of wheat powdery mildew. Such contrasting findings indicate that climatic effects are highly pathosystem-dependent and influenced by the thermal optimum, ecological niche, and adaptive capacity of individual pathogens. Therefore, climate change should not be interpreted as a universal driver of disease intensification but rather as a factor capable of generating diverse epidemiological outcomes depending on the biological characteristics of each host–pathogen interaction.

Taken together, the evidence demonstrates that climate change is reconfiguring the epidemiological foundations of plant diseases by modifying pathogen adaptation, host resistance, and environmental suitability simultaneously. This multifactorial process increases uncertainty regarding future disease outbreaks and highlights the need for integrated approaches that combine epidemiological surveillance, predictive modeling, plant breeding, and climate-informed disease management strategies.

4.2 Temperature, atmospheric CO₂, and humidity as drivers of disease severity and distribution

Among the climatic variables investigated, temperature emerged as the most influential factor affecting plant disease epidemiology (Figure 3). Evidence from the studies reviewed indicates that temperature directly regulates pathogen growth, reproduction, adaptation, and survival, thereby influencing both disease severity and geographic distribution. In *P. infestans*, Shen et al. (2022) demonstrated an association between thermal conditions, mitochondrial genome distribution, and pathogen fitness, suggesting that temperature acts as an important selective force shaping population structure. Similarly, Wu et al. (2020) reported rapid thermal acclimation responses, highlighting the capacity of this pathogen to adapt to changing environmental conditions over relatively short time scales.

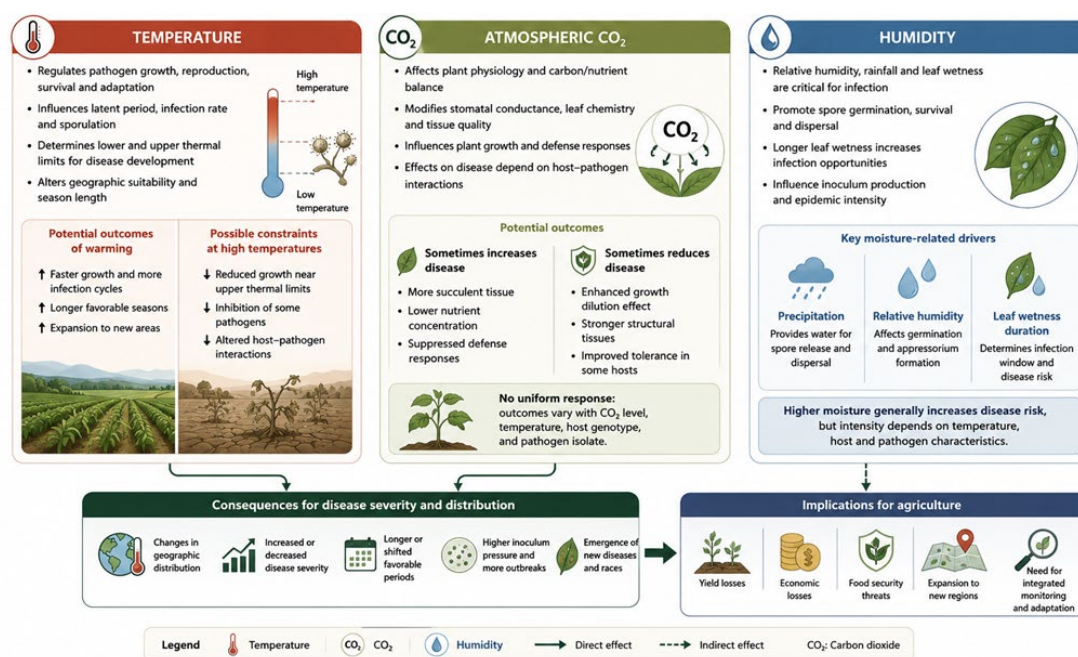


Figure 3. Climatic factors influence pathogens. AI source and verified by the authors, 2026.

These findings support the hypothesis that climate warming may accelerate pathogen adaptation and facilitate the establishment of disease outbreaks in new environments. However, the reviewed evidence also reveals important limitations to generalized assumptions regarding temperature effects. Although thermal increases may favor certain pathogens, they can also impose physiological constraints when environmental conditions approach or exceed species-specific thermal optima. Wu et al. (2020) observed that *P. infestans* growth tended to decline near its upper thermal threshold, while Matić et al. (2018) reported reduced development of wheat powdery mildew (*B. graminis* f. sp. *tritici*) under elevated temperatures. These contrasting responses indicate that climate warming is likely to generate both winners and losers among plant pathogens, depending on their ecological and evolutionary characteristics.

Atmospheric CO₂ concentration also emerged as an important but highly context-dependent driver of disease dynamics. Elevated CO₂ can modify plant physiology through changes in photosynthetic activity, biomass accumulation, stomatal conductance, nutrient allocation, and defense-related pathways. Nevertheless, the reviewed studies did not identify a consistent pattern of disease enhancement under elevated CO₂ conditions. Matić et al. (2018) found that disease development in wheat powdery mildew was influenced by the interaction between temperature and CO₂ rather than by elevated CO₂ alone. Likewise, Zou et al. (2019) demonstrated that disease severity in the *Brassica napus*–*Leptosphaeria maculans* pathosystem varied according to the specific host genotype–pathogen isolate combination. Together, these findings suggest that the effects of elevated CO₂ are mediated by complex physiological and genetic interactions, making disease outcomes highly dependent on the characteristics of individual pathosystems.

Humidity-related variables, including relative humidity, precipitation, and leaf wetness duration, were consistently associated with disease occurrence and epidemic risk. These environmental factors are particularly important for fungal pathogens because they directly influence spore germination, infection efficiency, inoculum production, and dispersal processes. Shabana et al. (2021) identified relative humidity as the meteorological variable most strongly associated with the occurrence of pathogenic and toxigenic fungi in wheat seeds. Similarly, Bebbier et al. (2016) demonstrated that leaf wetness duration and canopy temperature were key determinants of coffee leaf rust risk in Colombia, influencing the probability of germination and infection by *Hemileia vastatrix*.

Despite differences in methodology, both studies converged in recognizing moisture availability as a critical determinant of disease development. Shabana et al. (2021) employed observational and correlational analyses, whereas Bebbier et al. (2016) used epidemiological modeling based on climatic reanalysis data. The consistency of findings across these distinct methodological approaches strengthens the evidence that humidity-related variables play a central role in plant disease epidemiology. Moreover, projected changes in precipitation regimes and atmospheric moisture associated with climate change may substantially alter future disease patterns by modifying the duration and frequency of environmentally favorable infection periods.

Overall, the reviewed studies demonstrate that temperature, atmospheric CO₂ concentration, and humidity-related variables interact in complex ways to shape disease severity, pathogen adaptation, and geographic distribution. Rather than acting independently, these climatic drivers influence multiple biological processes simultaneously, reinforcing the need for integrated epidemiological models capable of predicting disease risks under future climate scenarios.

4.3 Emergence, geographic expansion, and vulnerability of agricultural systems

One of the most consistent findings among the studies reviewed was the influence of climate change on the emergence and geographic redistribution of plant pathogens. Alterations in temperature regimes, precipitation patterns, and atmospheric moisture create new environmental conditions that may favor pathogen establishment in regions previously considered unsuitable. Consequently, climate change is increasingly recognized as a major driver of disease emergence and epidemiological shifts in agricultural systems.

Singh et al. (2023) emphasized that climate change can modify pathogen biogeography, disease incidence, epidemic severity, and outbreak frequency across diverse cropping systems. This broad perspective is supported by predictive and observational studies included in this review. For example, Shahid et al. (2024) identified temperature seasonality, annual precipitation, precipitation during the driest month, and temperature during the wettest quarter as key determinants of the potential distribution of *D. zeae*, the causal agent of bacterial stalk rot in maize. Their findings suggest that future climatic conditions may expand suitable habitats for the pathogen, thereby increasing disease risks in regions not currently affected.

Similar conclusions were reported by Aslam et al. (2026) for wheat stripe rust caused by *P. striiformis* f. sp. *tritici*. The authors highlighted that warmer winters, altered rainfall patterns, and extended periods of leaf wetness may facilitate pathogen survival, increase inoculum pressure, and promote the emergence of more aggressive races. Together, these studies reinforce the notion that temperature and precipitation are among the most important climatic drivers of pathogen redistribution under future climate scenarios.

Evidence of disease emergence in newly affected regions was also reported by Lee et al. (2025), who documented the occurrence and prevalence of *Puccinia polysora* in maize-growing areas of South Korea. Although the study did not explicitly model climate change scenarios, its epidemiological observations contribute to understanding the expansion dynamics of rust pathogens and highlight the importance of continuous surveillance programs. When interpreted alongside the findings of Aslam et al. (2026), these results suggest that rust diseases may be particularly sensitive to environmental changes, increasing their potential for geographic expansion under changing climatic conditions.

Nevertheless, the relationship between climate change and disease risk is not always linear. Bebbler et al. (2016) demonstrated that predicted coffee leaf rust risk in Colombia varied substantially across years and regions. Although increased risk was detected during specific periods, particularly between 2008 and 2011, no consistent long-term increase was observed throughout the entire study period. This finding highlights the importance of considering interannual climatic variability, local environmental conditions, and microclimatic influences when assessing future disease risks.

Collectively, the evidence indicates that pathogen redistribution is a multifactorial process influenced not only by climate but also by host availability, pathogen adaptation, agricultural practices, and landscape characteristics. While there is broad agreement that climate change contributes to the emergence and expansion of plant diseases, the magnitude and direction of these effects vary considerably among pathosystems. Therefore, predicting future disease distributions requires integrated approaches that account for biological, environmental, and socioeconomic factors operating across multiple spatial and temporal scales.

4.4 Implications for phytosanitary management and agricultural adaptation

The studies reviewed consistently indicate that effective disease management under climate change will require the integration of epidemiological surveillance, climate information, predictive modeling, and adaptive agricultural practices. Traditional disease management approaches developed under historical climatic conditions may become less effective as environmental conditions continue to change, increasing the need for more resilient and flexible phytosanitary strategies.

Singh et al. (2023) emphasized the importance of strengthening monitoring networks, improving disease forecasting systems, and enhancing collaboration between scientific institutions and policymakers. Similarly, Savary et al. (2017) demonstrated that scenario-based analyses can provide valuable insights into future phytosanitary risks, particularly for globally important crops such as wheat. These approaches contribute to proactive disease management by identifying emerging threats before large-scale epidemics occur.

Host resistance remains one of the most promising adaptation strategies. Aslam et al. (2026) highlighted the importance of integrating resistant cultivars, race monitoring, agronomic practices, biological control, and fungicide applications to manage wheat stripe rust under increasingly variable climatic conditions. Comparable recommendations were proposed by Cohen et al. (2022) for the management of *Macrophomina phaseolina*, including the use of resistant rootstocks, grafting, irrigation management, planting-date adjustments, soil treatments, and the exploration of resistant germplasm.

The role of plant breeding was further emphasized by Silva et al. (2024), who argued that future breeding programs should prioritize climate-resilient genotypes capable of maintaining productivity and disease resistance under environmental stress. This perspective aligns with the review of Son & Park (2022), which highlighted the importance of understanding plant immune responses under elevated temperature, altered humidity, and increased atmospheric CO₂ concentrations. Together, these studies suggest that future crop improvement programs should integrate resistance to both abiotic and biotic stresses as complementary breeding objectives.

Biological control also emerged as a promising component of integrated disease management. Although Timmusk et al. (2019) did not directly investigate climatic variables, their findings demonstrated the antagonistic activity of biofilm polysaccharides produced by *Paenibacillus polymyxa* against *Fusarium graminearum*. Such approaches may become increasingly relevant as climate change alters pathogen populations and increases concerns regarding the sustainability of chemical control strategies.

Predictive modeling was another recurring theme among the selected studies. Bebber et al. (2016) and Shahid et al. (2024) demonstrated how climatic data can be incorporated into risk assessment frameworks to estimate infection probability and potential pathogen distribution. Although the studies differed in scale and objectives, both illustrate the growing importance of climate-informed epidemiological models for disease surveillance and agricultural planning.

Overall, the strongest consensus emerging from the literature is the need to integrate climate science, plant pathology, epidemiology, and crop management into comprehensive adaptation strategies. At the same time, the considerable variability observed among pathosystems highlights that no universal solution exists. Disease responses to climate change are highly dependent on crop species, pathogen biology, environmental conditions, and regional characteristics. Consequently, future phytosanitary adaptation efforts should be tailored to specific agricultural contexts, combining local knowledge with advances in climate forecasting, plant breeding, epidemiological modeling, and integrated disease management.

5. Conclusion

This integrative review demonstrates that climate change is fundamentally reshaping the epidemiology of plant diseases by altering the environmental conditions that govern host–pathogen–environment interactions. The evidence synthesized from the 17 studies reviewed indicates that climatic variables, particularly temperature, atmospheric CO₂ concentration, relative humidity, precipitation, and leaf wetness duration, significantly influence pathogen occurrence, disease severity, adaptation, dispersal, and geographic distribution.

Temperature emerged as the most influential climatic factor, affecting pathogen growth, survival, reproduction, and evolutionary adaptation. However, the reviewed studies revealed that climatic effects are highly pathosystem-dependent. While some pathogens may benefit from warmer conditions and expand into new geographic areas, others may experience physiological constraints or reduced disease development under elevated temperatures. These findings highlight the complexity of climate–disease interactions and underscore the limitations of generalized predictions regarding future disease risks.

The review further revealed that elevated atmospheric CO₂ and changes in moisture-related variables can modify both pathogen performance and host physiological responses, resulting in diverse epidemiological outcomes. In addition, the geographic redistribution of plant pathogens and the emergence of diseases in previously unaffected regions emerged as recurrent themes across the literature, suggesting that climate change will increasingly challenge existing phytosanitary management frameworks.

From an agricultural perspective, the findings emphasize the need to strengthen climate-informed disease surveillance systems, predictive epidemiological modeling, resistance breeding programs, and integrated disease management strategies. Future adaptation efforts should recognize the biological and environmental particularities of individual pathosystems, since disease responses to climate change vary according to crop species, pathogen characteristics, and regional climatic conditions.

This review also highlights important knowledge gaps. Most available studies focus on individual pathosystems and specific climatic variables, whereas the combined effects of multiple environmental drivers remain insufficiently understood. Future research should prioritize multidisciplinary approaches integrating plant pathology, climatology, genomics, epidemiological modeling, and agricultural management. Such efforts will be essential to improve disease forecasting, anticipate emerging phytosanitary threats, and support the development of resilient agricultural systems capable of sustaining productivity under future climate scenarios.

In conclusion, climate change should be recognized not merely as an environmental stressor but as a major driver of epidemiological transformation in plant disease systems. Addressing the challenges imposed by this process will require coordinated action among researchers, plant health professionals, policymakers, and agricultural stakeholders to enhance food security, protect crop production, and strengthen the resilience of global agricultural systems.

7. Authors' Contributions

Maria Vitória Gualberto Rodrigues: conceptualization, methodology, investigation, data curation, formal analysis, writing – original draft. *Lucas Carlos Leão*: investigation, data curation, literature search, formal analysis, writing – review & editing. *Fabircius Sousa Oliveira*: methodology, validation, formal analysis, visualization, writing – review & editing. *Marcelo Vaz de Oliveira* and *Aurélio Ferreira Melo*: supervision, validation, writing – review

& editing, project administration. *Matheus da Silva Santos* and *Porshia Sharma*: conceptualization, supervision, resources, writing – review & editing, project administration.

8. Conflicts of Interest

No conflicts of interest.

9. Ethics Approval

Not applicable.

10. Artificial Intelligence Statement: Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

The authors declare that generative AI and AI-assisted tools were used exclusively for the preparation of Figures 2 and 3. The AI-assisted figures were created using images and scientific information provided by the authors. No AI tools were used in the writing, editing, analysis, interpretation of data, or preparation of the manuscript text. Figures 2 and 3 were carefully reviewed, verified, and approved by the authors, who assume full responsibility for their accuracy and integrity. The use of AI is disclosed in the captions of Figures 2 and 3. AI tools are not authors and do not assume any responsibility for the content.

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