CLIMATE CHANGE IMPACTS ON PLANT DISEASES AND CROP PROTECTION

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Abstract

Climate change is considered one of the greatest threats to agriculture, resulting in significant yield losses and the loss of arable land due to various factors, ranging from unfavorable climate conditions to soil fertility issues. One significant aspect of climate change affecting crops is the development of diseases. The main factors of climate change affecting agriculture are the increase in temperature and CO_2 levels, as well as the alteration of precipitation regimes, which can lead to extreme weather events such as droughts and floods. These factors considerably affect pathogens' expression of disease in hosts, as well as their spatial and temporal distribution and life cycle limiting factors, which are now changing. Early studies show an increase in the severity and occurrence of diseases caused by pathogens in crops, a reduction in plant defense mechanisms, the emergence of new, adapted, and more aggressive pathogen strains, and a wider and faster expansion of pathogens. However, the efficacy of plant protection products is also reduced. However, each pathosystem is affected differently by climate change, and mitigating effects must be studied independently.

Key words: global warming; food security, plant pathogens, plant pathology

VPLIV PODNEBNIH SPREMEMB NA RASTLINSKE BOLEZNI IN VARSTVO RASTLIN

Izvleček

Podnebne spremembe veljajo za eno največjih groženj kmetijstvu, saj povzročajo znatne izgube pridelka in izgubo obdelovalnih zemljišč zaradi različnih dejavnikov, od neugodnih podnebnih razmer do vpliva na zmanjšanje rodovitnosti tal. Eden od pomembnih vidikov podnebnih sprememb, ki vplivajo na kmetijske rastline, je razvoj bolezni. Glavni dejavniki podnebnih sprememb, ki vplivajo na kmetijstvo, so povišanje temperature in ravni CO_2 ter sprememba režimov padavin, kar lahko privede do ekstremnih vremenskih pojavov, kot so suše in poplave. Ti dejavniki znatno vplivajo na izražanje bolezni patogenov pri gostiteljih, pa tudi na njihovo prostorsko in časovno porazdelitev ter dejavnike, ki omejujejo življenjski krog, ki se zdaj spreminjajo. Zgodnje študije kažejo povečanje resnosti in pojava bolezni, ki jih povzročajo rastlinski patogeni, zmanjšanje obrambnih mehanizmov rastlin, pojav novih, prilagojenih in agresivnejših sevov patogenov ter širše in hitrejše širjenje patogenov. Vendar pa se zaradi podnebnih sprememb zmanjša tudi učinkovitost fitofarmacevtskih sredstev. Podnebne spremembe različno vplivajo na patosisteme, blažilne učinke pa je treba preučiti neodvisno.

Ključne besede: globalno segrevanje, prehranska varnost, rastlinski patogeni, fitopatologija

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1 INTRODUCTION

Over the past 40 years, each decade has seen a greater increase in temperature than that observed since 1850. From 2011 to 2020, the average temperature rose by 1.09°C compared to the period 1850-1900, of which 1.07°C is attributable to human activity, with the remainder due to natural factors and internal variability. Projections indicate an expected increase of 1 to 5°C over the next 75 years (Intergovernmental Panel on Climate Change (IPCC), 2021). Precipitation has increased since 1950, with an acceleration since 1980. Humans are responsible for 65 to 100% of this increase and the change in ocean surface salinity. The intensity of storms in high latitudes in both hemispheres has also increased. According to various temperature increase models, the intensity of extreme precipitation will increase by 6.7 to 30.2% and will be 1.3 to 2.7 times more frequent than in the last ten years. On the other hand, droughts in agriculture are expected to be 1.7 to 4.1 times more frequent than in the last ten years (Dunn et al., 2020; Intergovernmental Panel on Climate Change (IPCC), 2021). Levels of carbon dioxide (CO_2) and nitrous oxide (N_2O) have been rising steadily since 1750 due to human activities, with increases of 47 and 23% respectively. Annual averages for CO_2 and N_2O rose from 391 ppm and 324 ppb in 2011 to 410 ppm and 332 ppb in 2019 (Intergovernmental Panel on Climate Change (IPCC), 2013, 2021). Various climate change scenarios show an accumulation of 1,000 to 4,000 $GtCO_2$ in the atmosphere between 2024 and 2100, due to less efficient carbon storage in the oceans and soils (Intergovernmental Panel on Climate Change (IPCC), 2022) . Due to climate change, the frequency of extreme weather events such as heat waves, heavy rainfall, droughts, and cyclones is increasing every year. Heat waves are more intense than in 1950, while extreme cold spells have become less frequent and less severe. Climate change has contributed to increased drought in agriculture in some regions, caused by increased evapotranspiration.

Today, climate change is considered one of the main threats to agricultural systems, particularly to food security, with potential yield losses (Pérez-Lucas et al., 2024). Despite the positive effect of increased CO_2 and higher rainfall on plant growth and yield, the adverse effects of extreme weather events such as heat waves, floods, or droughts far outweigh the “fertilization” effect of CO_2. As temperature, CO_2, and precipitation are the main factors influencing crop establishment and growth, pathogens and their host-parasite relationships are also profoundly affected by any climate change, positive or negative, and will determine the horizon for pathogen management in the coming decades. In recent decades, the frequency and impact of pathogens have increased significantly (Wood et al., 2018), but the mechanisms of pathogen pathogenicity, spread, and survival are not sufficient to explain the growing threat they pose. Since pathogens are closely linked to their hosts, it is necessary to study the impact of climate change on their host-parasite relationship and disease management.

2 CLIMATE CHANGE IMPACTS ON PATHOGENS

2.1 Pathogenicity

High temperatures generally promote the proliferation of plant pathogens (Tab. 1; Fig. 1), particularly fungi and bacteria, leading to more aggressive disease development (Lahlali et al., 2024). Rising temperatures can promote hyphal growth and disease severity, although there is an optimal temperature range that favours pathogen development and evolutionary adaptation (M. Wu et al., 2019; Sbeiti et al., 2023). Rising temperatures and elevated CO_2 levels (ECO_2) exacerbate the threat of late blight in potatoes (*Phytophthora infestans* (Montagne) de Bary), as well as serious rice diseases such as rice blast (*Pyricularia oryzae* Cavara) and sheath blight (*Rhizoctonia solani* Kühn) (Lahlali et al., 2024). Furthermore, the combination of increased CO_2 and temperature has been shown to increase the incidence of several plant diseases, including powdery mildew on zucchini (*Golovinomyces cichoracearum* (de Candolle) Heluta), *Alternaria* spp. leaf spot on arugula, black spot and downy mildew on basil (*Peronospora belbahrii* Thines), *Allophoma tropica* (R. Schneider & Boerema) Q. Chen & L. Cai on lettuce, and *Neocamarosporium betae* (Berlese) Ariyawansa & K.D. Hyde leaf spot on beets (Lahlali et al., 2024).

In the case of rice sheath blight (*R. solani*), inoculation of different cultivars, such as Lemont and YSBR1, revealed that increasing the temperature significantly increased the vertical length of lesions in Lemont (from 21 to 38%), while the effect on YSBR1 was minimal (from -1 to 6%). Interestingly, while ECO_2 had no effect on lesion length for either cultivar, the combination of high temperature and ECO_2 was associated with increased membrane lipid peroxidation, further exacerbating lesion severity. Despite the presence of ECO_2, which promotes biomass production by the plant, the negative impact of pathogens on plant yields was not mitigated. In the case of rice, for example, yield and biomass decreased by 2.0–2.5% and 2.9–4.2%, respectively, due to increased sheath blight under future climate conditions (Shen et al., 2023). In addition, high CO_2 levels have been associated with higher viral titers in plants, often leading to increased susceptibility to viral infections and a consequent increase in disease severity (Macháčová et al., 2024; Scandolera et al., 2024).

Precipitation is a key environmental factor that influences plant diseases by determining water and nutrient availability, soil moisture, pH levels, pesticide leaching, runoff, and inoculum formation and dispersal (Markovska et al., 2020; Lahlali et al., 2024). For example, increased precipitation can increase the frequency and severity of soil- and leaf-borne diseases such as root rot, damping-off, leaf spot, and downy mildew; the risk of flooding and waterlogging can create anaerobic conditions and promote the development of certain pathogens, such as *Pythium* spp. and *Phytophthora* spp. (Lahlali et al., 2024). Increased precipitation leads to higher humidity levels, which can have a significant impact on the occurrence and severity of leaf and fruit diseases caused by fungi and bacteria, such as anthracnose (*Colletotrichum* spp.), potato scab (*Streptomyces scabiei* (Thaxter) Lambert & Loria) and gray mold (*Botrytis cinerea* Persoon), as well as brown rust of winter wheat (*Puccinia recondita* Desmazières) (Markovska et al., 2020; Lahlali et al., 2024). Post-harvest diseases such as gray mold and soft rot (*Pectobacterium carotovorum* subsp. *carotovorum* (Jones) Hauben et al. of *Pandanus conoideus* Lam. fruits), which can cause significant losses during storage and transport, are promoted by increased humidity (Lahlali et al., 2024). In cases of low rainfall and drought, ear rot caused by *Aspergillus flavus* Link and *Fusarium* spp. are significant threats in maize fields (Lahlali et al., 2024). However, for certain diseases, such as Sclerotinia rot caused by *Sclerotinia sclerotiorum* (Libert) de Bary in kiwifruit and red needle cast in Radiata pine, drought may lead to a reduction in disease severity (Wakelin et al., 2018).

Moderate drought can increase disease severity in the host, while water replenishment after drought maintains pathogen severity in the host, particularly in stomatal conductance (Teshome et al., 2024).

2.2 Infectivity and propagation

Climate warming could also promote the overwintering and persistence of pathogens and insect vectors (Kobori & Hanboonsong, 2017; Lahlali et al., 2024; Mohanapriya et al., 2025). With higher winter temperatures, higher annual survival rates are predicted for pathogens such as *Phytophthora cinnamomi* Rands, whose survival rate has already increased in recent warmer years (Lahlali et al., 2024). Rising winter temperatures also alter the dispersal of pathogens across a territory, directly affecting their survival in new areas. Some pathogens have spread hundreds of kilometers over the past century, particularly near the Atlantic coast (Lahlali et al., 2024). However, high temperatures can reduce the performance of insect vectors in transmitting pathogens (Mohanapriya et al., 2025), as in the example of the transmission of cucumber mosaic virus in tobacco plants by aphids, which cannot be explained by the survival rate of the vector, but by its reduced transmission efficiency in high temperatures (Balagalla et al., 2025).

Precipitation plays a key role in leaf wetness duration, a crucial factor influencing infection and sporulation of many leaf pathogens. Increased precipitation tends to favour the development and spread of plant diseases, particularly those caused by oomycetes, while other diseases such as rusts, smuts, and powdery mildews are less common and spread under low humidity conditions (Lamichhane et al., 2024).

However, decreased rainfall may increase the use of irrigation, which can create favourable conditions (e.g., saturated soils) for certain diseases, such as bacterial wilt caused by *Erwinia tracheiphila* (Smith) Bergey et al. and root-knot nematodes caused by *Meloidogyne* spp. (Lahlali et al., 2024). Pathogens that thrive in drought conditions, such as causal agents of charcoal rot or fusarium wilt, which can affect various crops, including corn, sorghum, soybeans, sunflowers, and dry beans, can survive for years in dry soil and only a few weeks in moist, saturated soil (Lahlali et al., 2024; Teshome et al., 2024; Haddoudi et al., 2025).

Table 1: Impacts of climate change on pathogens. "+" indicates a positive impact for the pathogen, "-" indicates a negative impact for the pathogen, and "=" indicates no impact.

Climate change factor	Impact	Direction	Description	References
Increase of temperature	Pathogenicity	+	Higher growth and severity of disease; emergence of aggressive pathogen strains	(E. J. Wu et al., 2019; Sbeiti et al., 2023; Shen et al., 2023; Lahlali et al., 2024)
	Outbreak	+	Higher survival rates for pathogens and their insect vectors during the winter allow for dispersal into new, suitable areas	(Kobori & Hanboonsong, 2017; Lahlali et al., 2024; Mohanapriya et al., 2025)
	Outbreak	-	Insect vector's performance reduced	(Balagalla et al., 2025; Mohanapriya et al., 2025)
Increase of CO_2	Pathogenicity	+	Higher growth, occurrence and severity of disease	(Lahlali et al., 2024; Scandolera et al., 2024)
Increase of precipitation	Pathogenicity	+	Increased frequency and severity of disease; anaerobic soil conditions; post-harvest disease.	(Markovska et al., 2020; Lahlali et al., 2024)
	Outbreak	+	Inoculum formation and dispersal. Floods can spread pathogens over longer distances.	(Castroverde et al., 2015; Alcayna et al., 2022; Lahlali et al., 2024)
Decrease of precipitation	Pathogenicity	=/+	Drought increases the incidence and intensity of certain diseases	(Wakelin et al., 2018; Lahlali et al., 2024; Teshome et al., 2024)
	Outbreak	+	An irrigation system can favor the dispersal of pathogens and their survival in dry soil conditions	(Krauthausen et al., 2011; Alcayna et al., 2022; Lahlali et al., 2024)
	Outbreak	-	Reduced sporulation	(Lahlali et al., 2024)

3 CLIMATE CHANGE IMPACTS ON HOST-PATHOGEN INTERACTIONS

3.1 Dispersal of host

Not only do temperature changes alter agroclimatic zones, influencing host migration (Osland et al., 2023), but they may also promote the emergence of new pathogen complexes (Argüelles-Moyao & Galicia, 2024; Lahlali et al., 2024). The emergence of new strains is influenced by rising temperatures and increasing levels of CO_2 in the atmosphere (Pérez-Lucas et al., 2024), leading to rapid evolution of pathogenic strains. New strains create the possibility of new secondary hosts and are also better adapted to climate change, with even more aggressive strains (Sbeiti et al., 2023). The underlying mechanism for this rapid evolution is the increase in pathogen population and infection cycles, exposing more individuals to new climatic conditions in various hosts and growing areas (Lahlali et al., 2024).

The decrease in precipitation is expected to completely alter plant migration. As reduced precipitation and drought create unfavourable conditions for plants, humid and arid regions will change, leading to a decline in biodiversity in these areas (Fitzpatrick et al., 2008). The loss of biodiversity, as well as the low reproduction of host plants, will have a lasting impact on the spread of pathogens and their reservoirs for new strains. Decreased humidity can affect the quality and quantity of pollen and nectar, which can impact pollination and reproduction of host plants, with a change in the geographic distribution of host pathogens (Lahlali et al., 2024). However, waterborne diseases are expected to spread much more than vector-borne diseases, as extreme weather events such as floods become more frequent (Alcayna et al., 2022). Irrigation as a solution to drought can lead to the broad dissemination of pathogens in fields or greenhouses, particularly sprinkler irrigation, which increases water splashing among crops (Krauthausen et al., 2011). Meta-analysis revealed that pathogen will follow their hosts (especially wild plants), which are predicted to migrate around 6 km per decade on average (Chakraborty, 2013). Strong wind are part of extreme weather events that may reshape the migration of host and pathogen in the following years. Wind can for example disperse fungal spores such as wheat stem rust (*Puccinia graminis* Persoon) over thousands of kilometers (Castroverde et al., 2015).

3.2 Host defense mechanisms

Temperature is a key environmental factor that influences plant growth, development, and physiological processes. In addition, climate-induced changes in the phenology and physiology of host plants can make them more susceptible or more resistant to certain pathogens (Lahlali et al., 2024). Despite the potential gains in crop yields resulting from climate change, plant diseases may offset these gains. Heat and cold waves can induce thermal and oxidative stress in plants, compromising their photosynthesis and respiration and making them more susceptible to pathogens such as powdery mildew on grapevine (*Erysiphe necator* Schweinitz) and powdery mildew on zucchini (*Podosphaera xanthii* (Castagne) Braun & Shishkoff) (Gullino et al., 2018).

The role of temperature increase on phytohormone signaling pathways, particularly salicylic acid, has been demonstrated, reducing the accumulation of salicylic acid and other phenolic compounds in plants (Huot et al., 2017; Sivadasan et al., 2018; Rossi & Castroverde, 2024), while increasing the accumulation of jasmonic acid (Zhao et al., 2016). This response to heat is independent of pathogens and can lead to the suppression of callose deposition in plants.

Plants placed in an ECO_2 environment generally show greater growth in their aerial parts and a higher C/N ratio, linked to increased photosynthesis and instantaneous water use efficiency due to CO_2 "fertilization." These effects can often compensate for the loss of biomass due to pathogens (Scandolera et al., 2024). Under ECO_2 conditions, plants show increased resistance or greater sensitivity to pathogens depending on the pathosystem in question and various defense mechanisms. For example, the necrotrophic leaf pathogen *B. cinerea* induces resistance in its hosts when exposed to ECO_2, while a reduction in resistance to the hemibiotrophic leaf pathogen *Pseudomonas syringae* pv. *tomato* (Okabe) Young, Dye & Wilkie has been observed (Lahlali et al., 2024). Other host-pathogen relationships remain unchanged when exposed to ECO_2, as is the case with the soil pathogens *Fusarium oxysporum* f. sp. *raphani* Kendrick & Snyder and *R. solani*, which remained similar under all CO_2 conditions tested. The adaptation of defense mechanisms to ECO_2 can be observed in plant phenotypes, phytohormone signaling pathways, or the silencing of pathogenic RNAs. Increased CO_2 can induce higher or equal stomatal density, but reduce their conduction, which reduces the potential for infection by pathogens (McElrone et al., 2005). Any change in stomatal structure and function induced by increased CO_2 can affect the infection process. A loss of resistance to pathogens can also be observed with a significant increase in the level of membrane lipid peroxidation, associated with greater severity of fruit and leaf diseases, such as that caused by sheath blight (*R. solani*) on rice in ECO_2 (Lahlali et al., 2024). The results obtained on host defense signaling pathways highlight that CO_2 levels influence the accumulation of phytohormones, particularly the balance between salicylic acid- and jasmonic acid-dependent defenses, thereby affecting resistance against hemibiotrophic and necrotrophic leaf pathogens (Lahlali et al., 2024). ECO_2 appears to enhance the salicylic acid signaling pathway while decreasing that of jasmonic acid (Scandolera et al., 2024; Mohanapriya et al., 2025). The ABA phytohormones level does not seem to be altered in ECO_2 conditions in pathosystems. RNAi pathway on the defense response against virus under ECO_2 seems to be triggered as lower titer of virus RNA is found, however genes involved in the production of key cellular proteins used in the degradation of viral-derived dsRNA (Dicer-like, RNA-dependent RNA polymerase and Argonaute proteins) were downregulated in ECO_2.

In most pathosystems, one of the expected consequences of increased drought is an increase in disease expression. Increased precipitation and humidity appear to affect plant defense mechanisms, particularly secondary metabolites, with lower expression levels mainly in roots, which could lead to weakened phytohormone signaling, with JA accumulation being affected (Kharel et al., 2023). It is important to note that some diseases can benefit from drought conditions, as stressed plants become far less responsive to specific pathogens, leading to eased pathogen infestation. Decreased rainfall can also increase the susceptibility of host plants to water stress and other pathogens, such as *Fusarium* spp. and *Verticillium* spp., whose incidence and severity are increased (Manici et al., 2014; Lahlali et al., 2024; Haddoudi et al., 2025). Extreme weather events causing physical damage, physiological stress, and biochemical alterations in host plants, such as hail, can damage protective structures such as the cuticle and epidermis, making plants more vulnerable to diseases like downy mildew, bacterial spot, fire blight and crown gall pathogens (Lahlali et al., 2024).

Table 2: Impacts of climate change on host-pathogen interactions. "+" indicates a positive impact for the pathogen, "-" indicates a negative impact for the pathogen, and "=" indicates no impact.

Climate change factor	Impact	Direction	Description	References
Increase of temperature	Host dispersal	+	Host plant migration	(Chakraborty, 2013; Argüelles-Moyao & Galicia, 2024; Lahlali et al., 2024)
	Secondary host	+	Emergence of novel disease complexes and pathogenic strains	(Osland et al., 2023; Lahlali et al., 2024)
	Host defense	+	Physiological stress, oxidative stress, increased membrane lipid peroxidation levels, reduced salicylic acid accumulation, and increased jasmonic acid accumulation	(Zhao et al., 2016; Huot et al., 2017; Gullino et al., 2018; Lahlali et al., 2024; Rossi & Castroverde, 2024)
Increase of CO_2	Secondary host	+	Emergence of novel disease complexes and pathogenic strains	(Lahlali et al., 2024)
	Host defense	+	Physiological stress increases the level of membrane lipid peroxidation and disrupts the balance between salicylic acid- and jasmonic acid-dependent defense	(Gullino et al., 2018; Lahlali et al., 2024; Scandolera et al., 2024; Mohanapriya et al., 2025)
	Host defense	- / =	Increase in biomass and C/N ratio. Pathogen silencing RNA. Reduction in stomatal conduction	(McElrone et al., 2005; Scandolera et al., 2024)
Increase of precipitation	Host defense	-	Hailstorms can cause injuries that serve as entry points for pathogens	(Lahlali et al., 2024)
	Host defense	+	Impact on jasmonic acid accumulation	(Kharel et al., 2023)
Decrease of precipitation	Host dispersal	-	Drought affects the pollen and nectar of the host plant, which reduces its migration	(Fitzpatrick et al., 2008; Lahlali et al., 2024)
	Secondary host	-	Loss of biodiversity in wet and arid regions	(Fitzpatrick et al., 2008)
	Host defense	+	Drought stress increases disease severity because plants use resources for defense against abiotic factors	(Manici et al., 2014; Lahlali et al., 2024; Haddoudi et al., 2025)

4 CLIMATE CHANGE IMPACTS ON PLANT PROTECTION

Rainfall and high humidity can reduce the effectiveness of chemical treatments by decreasing their lifespan on sprayed leaves, and accelerate their degradation and leaching in soil (Ganchev & Ivanov, 2023; Lahlali et al., 2024). In case of increasing occurrence of extreme weather events such as infrequent heavy rainfall, decomposition of pesticides in soil will be impaired and will lead to an increase of leaching in ground waters (Aslam et al., 2015). However, biological control agents (e.g., *Beauveria peruviensis* D.E. Bustam., M.S. Calderon, M. Oliva & S. Leiva and *Metarhizium* sp.) are also enhanced and provide good pest control under conditions of high rainfall (Juarez-Contreras et al., 2025).

Table 3: Impacts of climate change on plant protection. "+" indicates a positive impact for the pathogen, "-" indicates a negative impact for the pathogen, and "=" indicates no impact.

Climate change factor	Impact	Direction	Description	References
Increase of temperature	Control measures efficacy	-/=	Biocontrol agents more active and efficient	(Gilardi et al., 2024; Lahlali et al., 2024; Evans et al., 2025)
Increase of CO_2	Control measures efficacy	- / =	Biocontrol agents more active and efficient	(Gilardi et al., 2024; Lahlali et al., 2024; Evans et al., 2025)
Increase of precipitation	Control measures efficacy	+	Chemical and biological control methods are less efficient. Faster degradation of products	(Aslam et al., 2015; Ganchev & Ivanov, 2023; Lahlali et al., 2024)
	Control measures efficacy	-	Higher pathogenicity of biocontrol agents	(Juarez-Contreras et al., 2025)
Decrease of precipitation	Control measures efficacy	=	Drought stress does not affect control agents	(Haddoudi et al., 2025)

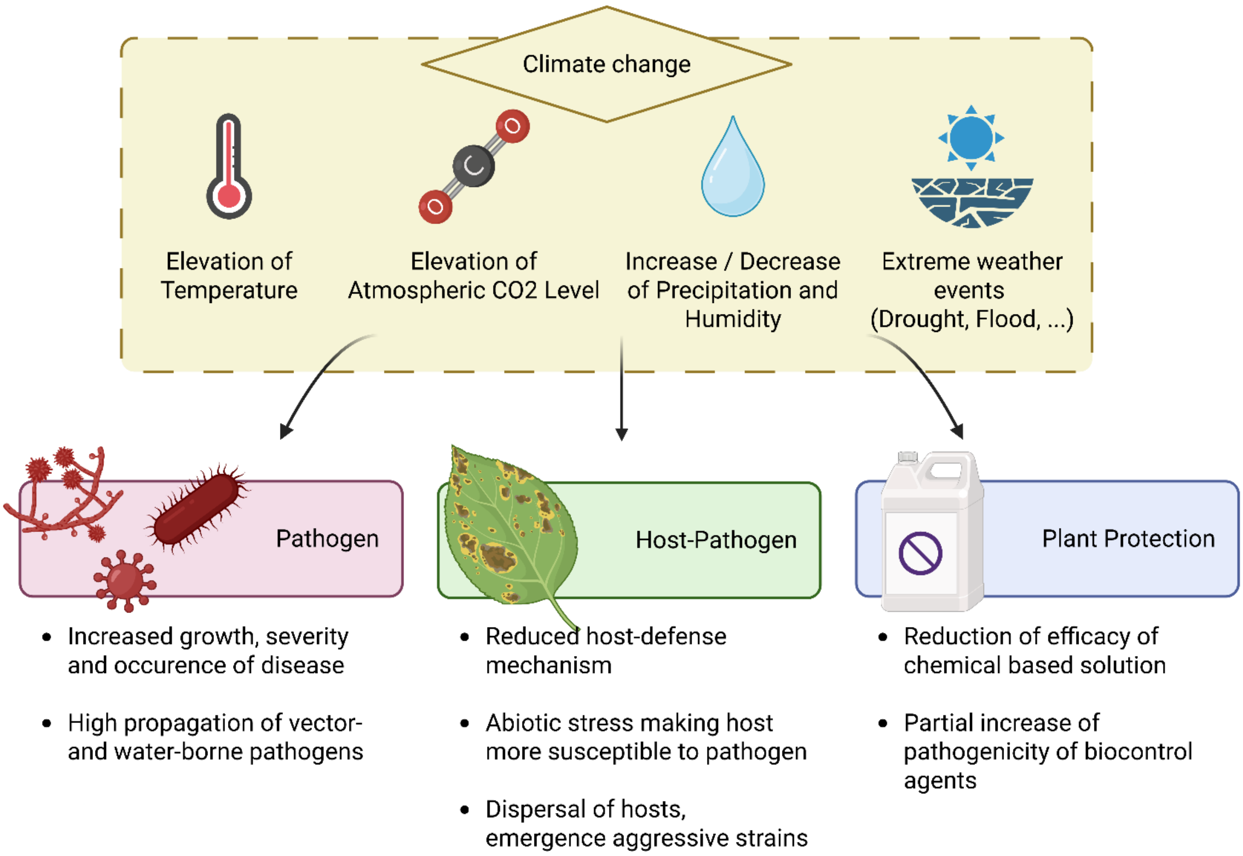

Figure 1: Main climate change factors affecting plant diseases and crop protection.

With regard to the application of biological control agents and resistance inducers, their effectiveness appears to be enhanced in most of the pathosystems studied in a scenario of global warming and increased CO_2 concentration (Evans et al., 2025). The effectiveness of *Ampelomyces quisqualis* Cesati against powdery mildew in zucchini has been shown to be enhanced under conditions of high temperature and ECO_2 (Lahlali et al., 2024). These results have been corroborated by the use of various biological control agents (i.e., *Streptomyces griseoviridis* Anderson, Ehrlich, Sun & Burkholder, *Trichoderma asperellum* Samuels, Lieckfeldt & Nirenberg, *Beauveria bassiana* (Balsamo) Vuillemin, and resistance inducers based on potassium phosphite and calcium oxide) on the lettuce-fusarium wilt pathosystem, with equal or improved control of the pathogen at high temperatures and CO_2 concentrations, up to 28°C, where biological control agents were ineffective (Gilardi et al., 2024).

The emergence of new, more aggressive strains is expected to be driven by rising temperatures and CO_2 levels. To combat these new strains, the focus should be on breeding new varieties that are resistant or more tolerant to them. These new varieties should also exhibit acute resistance to unfavorable abiotic conditions. On the other hand, forecasting and modeling pathogen migration and outbreaks need to be developed to better assess and mitigate risks. Some attempts have been made, such as with the pathogen *Xylella fastidiosa* Wells, Raju, Hung, Weisburg, Parl & Beemer, which was famously involved in the grapevine crisis in Europe. In conjunction with mapping and climate change scenario modeling, these attempts have identified high-risk areas that require close observation and integration into intensive plant protection programs (Alqahtani et al., 2025).

5 DISCUSSION

Studies on climate change affecting pathogens and pathosystems are already showing adverse effects on various crops, as well as beneficial effects on others. The impact of climate change appears uncertain for many pathogens, and each host-pathogen relationship must be assessed and rethought in order to cope with the new climatic conditions ahead. As agriculture gradually shifts toward less chemical-based plant protection, it is essential to include studies on biological control agents and the increasing complexity of crop diversity in the study of pathosystems. Crop models, which provide useful information on the ecosystem services provided by crops based on crop characteristics and climatic conditions, can be used as screening tools in the analysis of climate change impacts (Vercambre et al., 2024). When crop and pest models are coupled (i.e., pest density and severity are added to the crop model and interact with crop process functions), the impacts of climate change can be studied directly on pathogens within a specific crop (Lacroix et al., 2024). Models of soil-borne pathogen growth show that climate change will shift regions susceptible to certain plant fungal pathogens, particularly in northern Europe, while susceptibility to these pathogens will remain unchanged in Mediterranean countries (Manici et al., 2014). Studies on the local climate forecast for the coming years are needed to reshape agriculture in the context of climate change.

Therefore, breeding programs must incorporate climate-resilient resistance genes that are effective across a wide range of environmental conditions, particularly with regard to heat resistance and elevated CO_2. Additionally, these programs should consider epigenetic and physiological traits that facilitate stress adaptation because crops will face unfavorable abiotic conditions. To ensure effective plant protection in the future, agricultural practices must adopt climate-smart approaches. These approaches should include real-time monitoring systems, advanced forecasting models, and precision agriculture technologies. Decision support systems integrating weather data, pathogen modeling, and remote sensing could improve early warning capabilities and optimize intervention timing. Strengthening extension services, regional diagnostic networks, and international cooperation is essential for the proactive management of international pest and disease threats.

Data Availability

This article is a review and does not contain any original data. All data discussed in this review are available in the cited literature.

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