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Impact of Climate Change on Plant Diseases

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Abstract

Climate change is profoundly altering the dynamics of plant diseases, with significant implications for global agriculture and ecosystem stability. This review explores how rising temperatures, shifts in precipitation patterns, and elevated atmospheric CO_2 levels influence the incidence, distribution, and severity of plant diseases based on recent studies. Global temperature rise expands the geographic range of pathogens, including fungi, bacteria, viruses and oomycetes, while changes in moisture availability creates favorable conditions for both drought tolerant and water-dependent pathogens. Elevated CO_2 may further affect plant-pathogen interactions by altering plant growth and resistance mechanisms. Additionally, climate-induced phenological shifts are leading to changes in the timing and frequency of disease outbreaks. Therefore, understanding these complex plant-pathogen interactions are essential for developing adaptive management strategies, importantly, breeding of climate-resilient crops, disease forecasting models, and integrated pest management practices. Proactive efforts are critical to mitigate the increasing risks of plant diseases with the rapidly changing climate, globally.

Keywords: Agriculture, Climate change, Disease epidemiology, Mitigation strategies, Plant diseases

Introduction

Climate change refers to long-term alterations in temperature, precipitation, wind patterns, and other elements of Earth's climate system (IPCC, 2021). It is driven mainly by the emission of greenhouse gases from human activities such as burning fossil fuels and deforestation. These gases trap atmospheric heat, leading to rising global temperatures and shifting weather patterns. The consequences of human activities on world climate have reached an alarming state, posing critical threats to physical and socio-economic structures. The globally-averaged surface concentration of CO_2 reached 420.0 parts per million (ppm), methane 1,934 parts per billion (ppb) and nitrous oxide 336.9 ppb in 2023. These values are 151%, 265% and 125% of pre-industrial (before 1750) levels, respectively (WMO, 2024). Carbon dioxide emissions, which account for the maximum proportion of greenhouse gases (Sathaye *et al*., 2006), rose to 37.4 billion tons (Gt) in 2023 (IEA, 2024). The Intergovernmental Panel on Climate Change has projected that global temperatures will have a further increase of 1.5 °C between 2030 and 2052 (IPCC, 2014).

As mentioned by Mendelsohn (2009), agriculture is the most vulnerable sector to climate change due to its large scale and sensitivity to weather parameters, thereby causing huge economic impacts. While, pathogens and pests are major causes of crop losses and are responsible for estimated average global losses of 17.2 % to 30.0 % in staple crops (Savary *et al*., 2019). The interaction between pathogen, host, and

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environmental conditions, the components of the disease-triangle, is the key in determining the disease incidence. Climate change has a great effect on all these three factors (Zayan, 2019) by intensifying and broadening the impact of plant diseases through alterations in environmental conditions that favour the plant-pathogen interactions. Outbreaks of plant diseases affect both environmental sustainability and global food security by reducing primary production and biodiversity worldwide (Fones *et al*., 2020). Climate change may facilitate plant infection in multiple ways, including altering pathogen evolution, changing host–pathogen interactions and facilitating the emergence of new strains of pathogens, which in turn can break down host-plant resistance (Velásquez *et al*., 2018). Burdon and Zhan (2020) have also indicated that the plant diseases might proliferate into new regions as a result of pathogens shift their geographic ranges due to climate change.

Given the complexity and variability of plant-pathogen interactions, understanding the mechanisms by which climate change influences plant diseases are critical for developing adaptive management strategies. Thus, this review focused on exploring the current understanding of how climate change affects plant disease dynamics, focusing on shifts in pathogen distribution, changes in disease severity, and the interactions between environmental stress and disease susceptibility. Additionally, we will address the growing threat of plant diseases under changing climatic conditions.

Effect of climate change on the development of plant diseases

Elevated temperature

The temperature elevation is a crucial factor in disease development and severity as proven from various studies in the past. As indicated by Kweku *et al*. (2019), in a disease development the critical aspects of the pathogen infection process, such as latency period, sporulation, inoculum dissemination, and host resistance dynamics, are controlled by temperature. While, the reproduction and survival of pathogens are significantly influenced by temperature, which further influences the disease severity (Campbell and Madden, 1990). A recent study has shown that high temperatures encourage the growth and spread of plant diseases, particularly bacteria and fungi, while also retards host defensive systems (Devi *et al*., 2022). This impact of the elevated temperature in disease development and disease severity could be further analyzed with some examples from the past research works; wheat yellow rust started to appear in late December due to increased temperatures (Jindal *et al*., 2012). Regarding the interaction between the rust fungus *Puccinia striiformis* and wheat, new pathogen races that are more aggressive in causing disease at higher temperatures have appeared since the year 2000 and have become more prevalent worldwide in only a few years (Hovmøller *et al*., 2008; Milus *et al*., 2009). Stefansson *et al*. (2013) found that the local adaptation to stressful, high temperature as well as mean annual temperature variation in addition to a high adaptive potential for growth rate at all experimental temperatures in most populations of *Rhynchosporium commune*. When rice plants are pre-exposed to heat stress, their resistance to the fungal pathogen *Magnaporthe*

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oryzae is weakened, leading to faster tissue necrosis, increased pathogen proliferation, and more severe disease symptoms (Onaga *et al*., 2016). In southern Germany, a northward shift of *Cercospora beticola*, leaf spot of sugar beet was due to increase in the annual mean temperature by 0.8-1 °C (Saxony *et al*., 2011). On the other hand, the temperature rises in the environment also alter the host resistance factor. As an example, in *Arabidopsis thaliana*, high temperature reduces expression of the immune receptor FLS2, which suppresses immunity to the pathogen *Pseudomonas syringae* pv. *tomato* (Janda *et al*., 2019). Thus, the ability of pathogens to adapt to higher temperatures over time, along with reduced immunity in plants under heat stress, has led to an increase in disease incidence at elevated temperatures.

It is important to remember that there are differences in the ideal temperature range for pathogen-host systems, as certain pathogens can be sensitive to high or low temperatures (Porras *et al*., 2023). For example, temperature above 30 °C reduces the ability of spores of the fungal pathogen *Microbotryum lychnidis-dioicae*, which causes a sterilizing anther-smut disease on the herbaceous plant *Silene latifolia*, to germinate, grow, and conjugate *in vitro*, whereas temperature between 26 °C and 31 °C are ideal for papaya ring spot virus (PRSV) to infect papaya (Mangrauthia *et al*., 2009). *Xanthomonas oryzae* pv. *oryzae* (Xoo), that fails to efficiently colonize rice xylem when the daytime temperature exceeds 35 °C (Horino *et al*., 1982). These evidences showed that each pathogen has its preferred temperature for host-pathogen interactions to cause disease.

A more virulent and better-adapted strain of a pathogen may emerge due to rising temperature (Cohen and Leach, 2020). For example, fusarium head blight of wheat has re-emerged in the USA, favored by warm weather at anthesis (Chakraborty and Newton, 2011). Previous studies showed that increased temperatures can worsen the intensity of various crop diseases, including wheat rust (*Puccinia triticina*), rice blast (*Magnaporthe grisea*), potato late blight (*Phytophthora infestans*), and citrus canker (*Xanthomonas* spp.) (Ahmed *et al*., 2024; Singh *et al*., 2023). Tomato plants are more susceptible to tomato yellow leaf curl virus during heat stress (Anfoka *et al*., 2016). In Central America, warmer temperatures contributed to severe epidemics of coffee rust in 2012–2013, by increasing infection rates. In East Africa, rising temperatures have allowed rust to spread to higher altitudes, while in Southeast Asia, increased temperature have worsened coffee rust outbreak (Koutouleas, 2023; Toniutti *et al*., 2017).

Elevated carbon dioxide level

Elevated CO_2 levels cause physiological changes in plant morphology such as increases in leaf size, leaf thickness, and number of leaves (Pritchard *et al*., 1999). A thick canopy leads to increased duration of leaf surface moisture, presenting a highly favorable environment for spore germination and penetration in foliar pathogens (Garrett *et al*., 2006). However, enhanced plant growth may also create denser canopies and microclimates that favor pathogen proliferation, particularly for foliar pathogens that thrive in humid environments (Melloy *et al*., 2010). For example, enhanced canopy density increases leaf surface moisture retention and creates a favorable environment for pathogens like *Puccinia striiformis*, the causative agent of stripe rust. This pathogen thrives in high humidity and cool temperatures, leading to severe outbreaks under such conditions (Chen, 2005). In potato fields, dense canopies can trap humidity, creating a moist microclimate favorable for *Phytophthora infestans*, the late blight pathogen, relies on wet foliage to germinate and infect host tissues, leading to significant yield losses during humid seasons (Fry, 2008).

Plant immune responses and hormone levels are influenced by atmospheric CO_2 level, which can affect the plant-pathogen interaction. For example, increased basal expression of jasmonic acid-responsive genes under elevated CO_2 enhanced resistance to the necrotrophic leaf pathogen *Botrytis cinerea*, but reduced resistance to the hemi-biotrophic leaf pathogen *Pseudomonas syringae* pv. Tomato (Zhou *et al*., 2019). Reduction in the effectiveness of plant defense pathways under elevated CO_2 increased the susceptibility of wheat against the two major pathogens *Zymoseptoria tritici* and *Fusarium graminearum* that cause *Septoria tritici* blotch and *Fusarium* head blight, respectively (Váry *et al*., 2015). Elevated CO_2 levels increased the severity of powdery mildew on cucurbits caused by *Sphaerotheca fuliginea* (Khan and Rizvi, 2020).

Change in precipitation patterns

The change in precipitation patterns has diverse effects on the development of plant diseases. For instance, increased rainfall can increase the frequency and intensity of soil-borne and foliar diseases, such as root rot, damping-off, leaf spot, and blight (Lamichhane *et al*., 2023). Extended periods of leaf wetness due to increased rainfall increase the severity and rate of spread of soybean rust caused by *Phakopsora pachyrhiziin* (Narváez *et al*., 2010). In alfalfa, *Phoma medicaginis* is responsible for leaf spot and black stem diseases, which cause substantial yield reductions. The pathogen spreads to healthy plants through rain-splashed spores originating from infected plant debris (Lan *et al*., 2014). In groundnuts, wet weather promotes the spread of *Phaeoisariopsis personata*, the pathogen behind late leaf spot. This disease causes premature defoliation and leads to significant yield losses, particularly in areas with intense seasonal rainfall. Penet et al. (2014) found that direct rain splash dispersal being the dominant dispersal mechanism of *Colletotrichum gloeosporioides* conidia while re-splash from contaminated soil contributed less to dispersal.

Increased rainfall may also increase the risk of flooding and waterlogging, which can create anaerobic conditions, that favors the development of soil-borne pathogens, such as *Pythium* spp. and *Phytophthora* spp. (Martínez-Arias *et al*., 2022). Decreased rainfall may increase the susceptibility of host plants to drought stress and attack of pathogens, including *Fusarium* spp. and *Verticillium* spp. (Maurya *et al*., 2022). Drier conditions may also reduce the effectiveness of certain biological control agents such as *Trichoderma* spp. and *Pseudomonas fluorescens*, that rely on moist conditions for their survival, leading to increased disease prevalence (Harvell *et al*., 2002). *Pseudomonas fluorescens* is a well-known biocontrol agent against foliar and root diseases. It suppresses pathogens by producing antibiotics like 2, 4-diacetylphloroglucinol (DAPG) and siderophores that chelate iron. However, drier conditions limit the bacterium's ability to colonize the rhizosphere or leaf surface effectively, diminishing its ability to suppress pathogens such as *Phytophthora infestans* (Landa *et al*., 2002). Precipitation plays a major role in the dispersal mechanisms and spore germination of pathogens, as well as influencing plant disease management.

Change in humidity levels

The change in humidity levels is expected to have a significant impact on the development of plant diseases. Humidity significantly influences the formation and deposition of dew, providing a vital source of free water that facilitates the survival and infection processes of many plant pathogens (Nath, 2021). For example, higher humidity levels can increase the frequency and severity of foliar diseases such as leaf spot and fruit diseases such as anthracnose (*Colletotrichum* spp.), scab (*Streptomyces scabies*), and gray mold (*Botrytis cinerea*) (Ji *et al*., 2021; Maurya *et al*., 2022). Obanor *et al*. (2008) found that increased leaf wetness duration led to a higher number of *Spilocaea oleagina* conidia germination on olive leaves at all temperatures tested (5–25 °C). Increased humidity may also increase the risk of post-harvest diseases such as soft rot and stem end rot, which can cause significant losses in storage and transportation (Moradinezhad and Ranjbar, 2023). Infection rates by *Sclerotinia sclerotiorum* in lettuce (Mamo *et al*., 2021) and the stem rot pathogen *Phytophthora sojae* are higher under increased humidity (Tada *et al*., 2021).

High humidity significantly inhibits the accumulation and signaling of salicylic acid (SA), a key defense hormone in *Arabidopsis*. NPR1, an SA receptor and co-activator of SA-responsive genes, is less ubiquitinated and has a reduced affinity for promoter binding under high humidity, which increase disease susceptibility in *Arabidopsis*. The down regulation of the cellular ubiquitination machinery, particularly the Cullin 3-based E3 ubiquitin ligase, impairs NPR1 protein ubiquitination in these conditions (Yao *et al*., 2023). Humidity significantly influences plant disease outbreaks, with high ambient humidity enhancing rice blast development caused by *Magnaporthe oryzae*. Study showed that increased humidity promotes conidial germination and appressorium formation, boosting the pathogen's virulence. High humidity suppresses ethylene biosynthesis and signaling, which are critical for basal resistance in rice. These findings highlight that humidity compromises rice resistance by reducing ethylene pathway activation (Qiu *et al*., 2022). Decreased humidity may reduce the incidence and spread of some diseases, such as rust and smut, but may also increase the susceptibility of host plants to water stress and other diseases such as wilt and canker (Jeger, 2022). A study by Milod et al. (2021) revealed that low relative humidity (20–40 %) and high temperatures (30 °C or above) inhibited disease progression of cucumber powdery mildew caused by *Erysiphe cichoracearum*. Humidity level affects plant diseases by promoting pathogen activity and suppressing plant defenses at high levels, while low humidity inhibits some pathogens but increases stress susceptibility.

Extreme weather conditions

Severe weather conditions cause physical damage, physiological stress, and biochemical changes in host plants, and it is one of the main environmental factors influencing plant diseases (Singh *et al*., 2023). Extreme weather conditions increase the susceptibility of host plants to diseases. For instance, storms can cause physical wounds on host plants, serving as entry point for pathogens causing various diseases such as crown gall, rust and Aphid-transmitted viral diseases (Bastas, 2022). Extreme weather events can help spread of pathogens to new locations, as for the case of soybean rust, which was introduced from Brazil into the United States by a hurricane (Fones *et al*., 2020). *Fusarium oxysporum* f. sp. *cubense* Tropical Race 4, a new race of the causal agent of Fusarium wilt of banana, may have been spread in Mozambique by a cyclone, increasing the risk of further spread to adjacent farmlands and neighboring countries in Africa (García-Bastidas *et al*., 2014).

Flooding can also rapidly spread many pathogens among adjacent farms and regions. Pathogens with flagella or swimming stages, such as the oomycete pathogen *Phytophthora*, and *Ralstonia solanacearum* are able to disperse rapidly through flooded regions to new susceptible plants (Browne *et al*., 2021; Feng *et al*., 2017). Heat waves and cold snaps may induce heat and oxidative stress in plants, compromising their photosynthesis and respiration and rendering them more susceptible to diseases such as leaf spot, and black rot (Tanveer *et al*., 2023). In addition, hail damage to protective layers such as the epidermis and cuticle can make plants more vulnerable to diseases like bacterial spot and downy mildew (Khadiri *et al*., 2023). These studies showed that extreme weather events significantly influence plant diseases by causing physical damage, spreading pathogens, and increasing plant susceptibility through stress and weakened defenses. Events like storms, floods, and temperature extremes facilitate pathogen dispersal and infection, intensifying the risk of disease outbreaks from one geographic region to another.

Adaptation Strategies for Agriculture

Breeding for disease-resistant crops

A key adaptation strategy to combat plant diseases under climate change is the development of disease-resistant crop varieties. Recently, the CRISPR/Cas9 system has been utilized to enhance disease resistance among different crops such as rice, cacao, wheat, tomato, and grapes (Ahmad *et al*., 2020; Brooks *et al*., 2014). This system allows for precise genome editing of various organisms via RNA-guided DNA endonuclease activity. In soybean, Nagy et al. (2021) utilized CRISPR/Cas9 to develop a novel chromosome rearrangement method. This approach engineered two NLR gene clusters, Rpp1-like, conferring resistance to *Phakopsora pachyrhizi*, and Rps1, associated with resistance to *Phytophthora sojae*. This technique demonstrated a promising strategy for enhancing disease resistance in soybean. In the cacao tree (*Theobroma cacao*), genome editing was conducted using *Agrobacterium*-mediated transient transformation to introduce CRISPR/Cas9 components that targeted non-expressor pathogenesis-related 3 (*TcNPR3*), a suppressor of the defense response, into cacao leaves and cotyledon cells. The *TcNPR3* deleted leaves exhibited up-regulated expression of defense genes, such as pathogenesis related (PR) genes, and enhanced resistance to the black pod disease caused by *Phytophthora tropicalis* (Fister *et al*., 2018).

Beyond genome editing in crops, editing the genomes of fungal and oomycete pathogens can also provide new strategies for plant disease management (Paul *et al*., 2021). The CRISPR/Cas9 method was used for directed mutagenesis targeting pyrimidine biosynthesis and tryptophan biosynthesis genes (pyr4 and TrpE) of biotrophic plant pathogen *Claviceps purpurea*. The TrpE mutants showed no infection to rye plants because of a reduction of the plant hormone auxin, which is normally synthesized by *C. purpurea* in Trp-dependent and Trp-independent biosynthetic pathways, ultimately affecting the ability of the fungus to colonize rye plants (Králová *et al*., 2021). Homozygous *PpalEPIC8* mutants of the papaya pathogen *Phytophthora palmivora* were created using the CRISPR/Cas9 system, and it was observed that these mutants showed decreased ability to cause disease in papaya fruits. This reduction in pathogenicity occurred because the deletion of the cysteine protease inhibitor *PpalEPC8* led to a diminished suppression of papain, a cysteine protease in papaya that plays a role in defending against plant pathogens (Gumtow *et al*., 2018).

These methods can create crops that are more resilient to the changing pathogen pressures brought about by climate shifts. Panwar et al. (2018) demonstrates that generating transgenic wheat plants expressing RNAi-inducing transgenes to silence essential genes in rust fungi (*Puccinia triticina*) can provide effective disease resistance, thus opening an alternative way for developing rust-resistant crops. Tiwari et al. (2017) enhanced the resistance of rice to the sheath blight disease by down-regulating pathogenicity genes of *Rhizoctonia solani* using host-delivered RNAi. Ding et al. (2021) found that the appressorium-related gene *Sscnd1* is required for cell integrity and full virulence in *Sclerotinia sclerotiorum* and that Sclerotinia stem rot can be controlled by expressing the silencing constructs of *Sscnd1* in host plants. These techniques pave the way for breeding disease-resistant crops in order to overcome challenges from climate change in agriculture.

Improved forecasting and monitoring systems

Predictive modeling and disease forecasting tools have become essential in anticipating the emergence of plant diseases under varying climate conditions. Climate-based forecasting systems help in the early detection of disease outbreaks, enabling timely interventions (Elad and Pertot, 2014). Optical techniques, such as RGB imaging, multi- and hyperspectral sensors, thermography, or chlorophyll fluorescence, have proven their potential in automated, objective, and reproducible detection systems for the identification and quantification of plant diseases at early time points in epidemics (Mahlein, 2016). Chlorophyll Fluorescence Imaging (CFI) is used to detect disruptions in photosynthesis. Chlorophyll Fluorescence Imaging has proven effective for identifying diseases like *Xanthomonas* infections in *Arabidopsis* at early stages. This technique relies on changes in fluorescence emission caused by stress, enabling a detailed study of pathogen effects (Sapoukhina *et al*., 2022). Oerke et al. (2011) and Belin et *al*. (2013) analyzed apple trees suffering from apple scab. In that case, the detection of infection, as well as differences in the virulence of several *Venturia inaequalis* isolates infecting apple trees, were detected more accurately by thermography. The thermal response was presymptomatic and consisted of spots of decreased temperature due to the subcuticular growth of *V. inaequalis*.

There has been a substantial effort to develop smart agricultural tools to help address the uncertainty surrounding plant disease epidemics through computational decision support systems (DSSs) (Zhai *et al*., 2020). AgroClimate is one of the example of a DSS designed to tackle weather- and climate-based risks in agriculture (Fraisse *et al*., 2016). AgroClimate provides several tools to assist farmers with plant disease management. The strawberry (Pavan *et al*., 2011), blueberry (Gama *et al*., 2021), and citrus advisory systems (Perondi *et al*., 2020) couple current and forecast weather data with disease models to predict risks and recommend fungicide applications when environmental conditions are favorable for disease development.

Cultural practices and agronomic adjustments

Agronomic adjustments, such as crop rotation, intercropping, soil tillage, altered planting dates, and liming and irrigation are important adaptation strategies to prevent or reduce the risk of diseases (Fry, 2012). These practices can reduce the environmental conditions favorable for pathogen proliferation. Enhanced diversity in cropping systems may reduce the risks of diseases that otherwise, in monoculture, would become more severe due to climate change. For example, Hannukkala et al. (2007) concluded that increased and earlier occurrence of late blight (*Phytophthora infestans*) epidemics in potato were probably associated with both climate change and lack of rotation.

Mitigation Strategies

Reducing greenhouse gas emissions from agriculture

Mitigation strategies aim to address the root cause of climate change by reducing greenhouse gas (GHG) emissions from agricultural practices. Agricultural activities, such as the use of synthetic fertilizers and livestock production, significantly contribute to the global GHG emissions (Smith *et al*., 2014). By implementing sustainable agricultural practices, such as organic farming, conservation agriculture, and the use of bio-fertilizers, farmers can reduce emissions and minimize the long-term impacts of climate change on plant diseases (Lal, 2004).

Carbon sequestration through agroforestry

Agroforestry, which integrates trees into agricultural landscapes, provides a dual benefit in both climate mitigation and disease management. Trees sequester atmospheric carbon, reducing the overall greenhouse gas burden (Jose, 2009). At the same time, agroforestry systems promote biodiversity, which can suppress the spread of plant diseases by creating more complex ecosystems that limit pathogen proliferation (Schroth *et al*., 2000). Vertical stratification of soil carbon stock under agroforestry is one of the options for long-term carbon sequestration and mitigating GHG emissions (Mishra *et al*., 2024).

Integrated pest management

Integrated Pest Management (IPM) is a holistic approach that combines biological, cultural, and chemical tools to manage plant diseases in a sustainable manner. Integrated Pest Management reduces the reliance on chemical pesticides, which are known to contribute to greenhouse gas emissions and can exacerbate environmental issues (Lamichhane *et al*., 2016). By incorporating climate-resilient practices, IPM can minimize disease outbreaks while promoting environmental sustainability.

Biotechnological approaches for climate-smart agriculture

Biotechnology, including genetic engineering and the use of microbial inoculants as biocontrol agents, offers promising solutions for managing plant diseases under climate stress. Genetically engineered drought-tolerant maize varieties, such as *MON 87460* (developed by Monsanto), utilize genes like *cold shock protein B* (cspB) from *Bacillus subtilis*. These maize varieties are widely adopted in sub-Saharan

Africa to mitigate yield losses due to water scarcity (Nemali *et al*., 2015).

Recent advances in plant-microbiome research have shown that manipulating the rhizosphere microbiome can enhance plant resistance to both biotic and abiotic stresses (Compant *et al*., 2019). Targeting Induced Local Lesions in Genomes (TILLING) is a reverse genetic technique based on chemical induced mutagenesis coupled with a sensitive DNA screening-technique (Slade and Knauf, 2005) which allows the discovery of rare mutations in populations. Barley mutants were generated by TILLING to study the nucleotide variations in the *era1* (enhanced response to ABA1) gene (Daszkowska-Golec *et al*., 2018), which is differently regulated under drought tolerance in several species including wheat and soybean (Manmathan *et al*., 2013; Ogata *et al*., 2017).

Extremophiles are the microorganisms thriving in extreme environments apparent with harsh conditions such as thermophilic (high-temperature), psychrophilic (low temperature), halophilic (hypersaline environment), acidophilic (low pH), alkaliphilic (high pH), piezophilic (high pressure/deep sea), radiophilic (high radiation), xerophilic (no water), anaerobes (absence of oxygen), and snottite (in caves), and where normal life does not exist (Passarini *et al*., 2022). This can be utilized to combat complications faced by the agriculture sector in response to climate change as these genes which are responsible for their superior character can be incorporated into plant genome in order to produce stress resistant crop varieties.

Genome selection is an innovative tool in plant breeding to speed up crop improvement and high-throughput phenotyping to identify climate-resilient genotypes for future breeding (Tadesse *et al*., 2019). Climate-smart potato clones have been developed which showed high resistance to drought and heat stresses without yield penalty. The conditions given to these clones were 2–3 °C increases in temperature and about 15-20% lower precipitation under the scenario of climate change (Parker *et al*., 2019).

Challenges and future directions

Although various adaptation and mitigation strategies show promise, several challenges remain. Climate change projections are inherently uncertain, making it difficult to predict the exact nature and magnitude of future plant disease outbreaks. Moreover, the global disparity in technological and financial resources can hinder the implementation of climate-resilient agricultural practices, particularly in developing nations (Nelson *et al*., 2009). Collaborative efforts between governments, research institutions, and farmers will be necessary to develop context-specific solutions that address these disparities and enhance global food security. Further research is needed to understand the complex interactions between climate change, plant physiology, and pathogen behavior. Integrating knowledge from plant pathology, climate science, and agricultural economics will provide a more comprehensive framework for tackling plant disease epidemics in a changing climate.

Conclusion

The impact of climate change on plant diseases is a complex and multifaceted issue that poses significant risks to agriculture and ecosystems. Changes in temperature, precipitation, and atmospheric CO_2 levels influence the biology of both plants and pathogens, potentially increasing the prevalence and severity of plant diseases. To address these challenges, proactive measures that integrate climate change considerations into plant disease management practices are necessary. Continued research and collaboration are critical for developing resilient agricultural systems that can withstand the increasing pressures of climate-induced plant diseases.

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