



Climate change and its role in plant health and disease dynamics

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Summary

Climate change is due to the concentration of greenhouse gases (CHG) and increased human activity. It is projected that CO₂ concentration and temperature will rise to 1250 ppm and 3.4 °C, respectively, by 2095. In changing climatic conditions, most cereal, vegetable, and fruit crops are affected by biological and non-biotic factors. Changes in climatic variables directly affect the distribution and migration pattern of diseases, reproduction and development of pathogens, breaking of host plant resistance, decrease in survivability of bioagents, lowering the population of natural enemies, affecting endophyte–plant interactions, and affecting the efficacy of pesticides by changing of plant morphology. This overview focuses on discussing various aspects of the climate factors affecting plant disease.

JAE 2025, Vol 20

Received: 25 March 2025

Accepted: 20 April 2025

Published: 07 June 2025

<https://doi.org/10.58628/JAE-2520-102>

Associated Editor: Dr. B. Sinha

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Keywords: Climate change, temperature, CO₂, bioagent, pest adaptation, plant diseases

Introduction

Most of the agricultural crops used for food purposes are affected by various pests, diseases, and extreme climatic conditions. Various reports have shown that on per year (Agrios 2005). Plant disease is the result of interactions with susceptible host plants, toxic pathogens, and the environment. Climate change is the result of continuous increases in temperature and CO₂ concentrations. Temperature and CO₂ concentrations are predicted to increase by 3.4°C and 1250 ppm by 2095 (Savary et al. 2012). This impact can be felt primarily in developing countries such as India. In India, loss of agricultural production due to extreme weather related to climate change, due to malnutrition, poverty, and related diseases, contributes to death (Gautam 2013). Climate change directly or indirectly affects plants, pathogens, and their microbial antagonists. Climate conditions are vigorously associated with different losses caused by disease, and are often involved in the development of new diseases (Anderson et al. 2004). Changes in climatic variables, such as these, can affect tavern interactions and also the spatial and temporal development of disease epidemics (Chakraborty 2005; Crowl et al. 2008; Eastburn et al. 2011). Understanding the impact of various climate change changes on disease dynamics is important for the introduction of appropriate management practices and disease resistance (Chakraborty & Pangga 2004; Ghini et al. 2008). Various climatic variable studies were conducted regarding disease distribution, disease development, interactions between tavern pathogens, organic regulatory components, host system resistance, and pesticide efficacy. Climate change affects plant disease along with anthropogenic processes such as air, water, soil pollution, remote areas of exotic species, and

36.5% of crop production is mainly affected by diseases, insects, and weeds. A total of 14.1% of harvest losses are due to disease outbreaks, which corresponds to a loss of USD 2220 billi urbanization (Regniere 2012). These climatic factors are involved in the sudden spread of disease (Prospero et al. 2009). Increased CO₂ and temperature affect plant disease interactions, representing a higher threat to the rice and blast (*Phytophthora Infestans*) of potatoes, vague (*Rhizocctonia solani*) and blast (*Magnaporthe grisea*) (Kobayashi et al. 2006). The effects of climate change on Phoma (*Leptosphaeria Macran*) in rape seeds were observed by a model combined with climate change and precipitation in the UK's 2020 and 2050s CO₂ emission scenarios (Evans et al. 2007) and telomorph sporulation on climate change (Kaczmarek et al. 2016). The purpose of this review is to report and discuss the specific relationships between the effects of climate change on the spatial and temporal distribution of plant diseases, increased concentrations of atmospheric CO₂, disease development, biological control, host plant resistance, specific relationships among plant pathogens, and pest control.

Effect of climate on disease distribution/migration

Distribution of diseases from one location to another can be influenced by climatic factors. Changes in the geography of both wilder and cultivated plant species probably have the most dramatic effect on plant disease, as new associations significantly increase the likelihood that new pathogen associations will form and some of them will become more serious. New diseases may occur in certain regions, and if the host migrates to a new region, other diseases may cease (Coakley et al. 1999). During migration, host plant pathogens continue to their geographical distribution, but the rate at which pathogens determine in the new environment depends on the mechanism of pathogen trends, the compatibility of the environment of spreading, and the

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physiological and ecological changes of the host plant. According to Chakraborty et al. (2000), more aggressive pathogens can be hiked from agro ecosystems to natural vegetation in a wide range of host plants such as *Rhizoctonia*, *Sclerotinia*, and *Sclerotium*, and less aggressive pathogens from natural plant communities can cause monoculture damage in nearby areas. *Puccinia striiformis* f. sp. *tritici* (PST), a pathogenic wheat pathogen with global prevalence and great potential for long distance hiking, represents a threat of serious invasion to new regions (Dean et al. 2012; Beddow et al. 2015). This pathogen can be considered a cold loving pathogen (Brown & Hovmoller 2002), but it has recently been reported that this fungus has penetrated the warm areas of wheat varieties. In India, the temperature-loving variety of *Pst* 78S84 has broken resistance from R-gene YR9 and YR27 with PBW 343 wheat mega varieties from the north western region of India. Similarly, Panama disease (*Fusarium oxysporum* f. sp. *cubense* race 1) *Foc*TR4 Central American banana industry was wiped out with Cavendish banana in planting materials as a new focus on lace emerged. These infected plant materials distributed this pathogen in Laos, Myanmar and Vietnam. This spread from Southeast Asia to the Indian subcontinent, the Middle East and Africa (Ordóñez et al. 2015; Zheng et al. 2018; Maheshwari et al. 2022). *Uromyces ciceris-arietini* Jacz. has recently spread from chickpeas (*Cicer arietinum*) to Europe (Bulgaria, Cyprus, France, Corsica, Greece, Hungary, Italy, Sicily, Portugal) (Cab, International, 2020). Tomato leaf curl New Delhi virus (Geminiviridae: Begomovirus) distributed in Europe (Estonia, Greece, Italy, Mainland Italy, Sardinia, Sicily, Portugal, Azores, Mainland Portugal, Spain), *Pseudomonas syringae* pv. *tomato* (Okabe) and chilli (*Capsicum annuum*) spread in Austria and Belgium (CAB, International, 2020). Phoma stem canker (*Leptosphaeria maculans*) is an internationally important disease of wild and cultivated brassicas, which causes yield losses of millions of tonnes in brassica and vegetable crops after spreading in Europe, North America, Australia, and Africa (Fitt et al. 2006). The yellow dwarf virus from barley is available in North America, Ecuador, China, Pakistan and Northern Europe. Drought increases aphid survival and spread. In Pakistan, it has been observed that in some years, dry air favors aphid flights. Warmer temperature increases the transmission rate of the invasive pathogens, as suggested by Robinet et al. 2011. Navas-Castillo et al. (2011) studied whiteflies that transmitted viral diseases and reported the appearance of tomato yellow leaf curl disease, cassava mosaic disease, cucurbits virus diseases, tomato chlorosis, and the torrado-like diseases of tomato in various growing regions.

Effect of climate on disease development

Climatic factors such as temperature, relative humidity (RH), moisture, and CO₂ concentration affect the disease development. Due to changes in temperature and precipitation systems, the development rate, growth stage, plant physiology, pathogen pathogenicity and resistance mechanism in plants may be affected

climate change (Chakraborty et al. 1998; Chakraborty & Datta 2003).

a). Temperature

Different hidden pathogens could induce an epidemic in favourable temperature conditions. Increased temperatures with sufficient soil moisture can increase evaporation transitions, leading to a wet microclimate in the plant, which can lead to the development of diseases preferred under these conditions (Mina & Sinha 2008). Temperature affects the development of bacterial diseases such as *Ralstonia solanacearum*, *Acidovorax avenae*, and *Burkholderia glumea*. These bacteria grow in areas where temperature-dependent disease has not been observed (Kudela 2009). Temperature changes, especially ambient temperature (Li et al. 2013) affect microbial pathogens, and disease incidence (Suzuki et al. 2014, Ashoub et al. 2015). Various rust resistance genes, i.e., Pg3 and Pg4 of oat stem, Lr210 and Lr217 of wheat leaf, are temperature sensitive and become susceptible to the temperature influence (Das et al., 2016). The global average temperatures are expected to rise around 1–2 °C by the year 2100. Simultaneously, the more frequent occurrence of high temperatures, storms, or drought has also been projected (Cook et al. 2016). The changes will affect the virulence (Garrett et al. 2011), distribution, and emergence of pathogens in new areas (Albouy et al. 2014; Sinha et al. 2023). In India, temperatures adversely affect dry root rot disease of chickpea caused by *Rhizoctonia bataticola* and blight disease of pigeon pea caused by *Phytophthora drechsleri* f. sp. *cajani* in India (Pande & Shanna 2010). More risk of dry root rot disease in the chickpea variety resistant to *Fusarium* wilt with temperatures more than 33°C was also reported by Dixon 2012. Vector-borne diseases have also been adversely affected by climatic conditions. Climatic factors influence their development and distribution in different regions. According to Navas-Castillo et al. (2011) viral diseases transmitted by whiteflies were quickly transferred in healthy plants from diseased plants under a different range of temperatures and play a potent role in the transmission of tomato yellow leaf curl disease, cassava mosaic disease, cucurbits virus diseases, and chlorosis diseases of tomato. The rise in temperature, coupled with humidity, influences the susceptibility of wheat which leads to the infection of *P. recondita*, which causes brown rust disease. Due to increased temperature, wheat yellow rust has started appearing in late December (Prashar et al. 2007; Jindal et al. 2012). The UG99 race of stem rust, a new threat to wheat production, has entered the Middle East and presents the potential for wide-scale yield losses. Leaf rust caused by *Puccinia tritici* is present in North and South America, Europe, North Africa, Russia, the Middle East, and the Indian Sub-continent. In South Asia, the disease tends to appear late in the growing season when the temperature is rising. Climate change can lead to disease spread in areas where its importance is minor at present, facultative and winter wheat growing areas of China, parts of Europe, the Pacific Northwest of US,

and winter and facultative wheat areas of Central Asia. Temperature is one of the most important factors affecting the occurrence of bacterial diseases such as *Ralstonia solanacearum*, *Acidovorax avenae* and *Burkholderia glumea*. These bacteria proliferate in the area where they were previously not confined. The incidence of powdery mildew and foliar blights has also increased in the northern regions of India. Powdery mildew has been predicted to cause serious losses in winter wheat in China under simulated elevated temperature conditions (Tang et al. 2017). Rice blast disease was not present in Punjab before the year 2000 however, neck blast has become a serious problem in Basmati rice in recent years. Citrus Greening disease, transmitted by *Diaphorina citri* Kuwayama (Homoptera: Psyllidae) 'Asian Citrus Psyllid' transferred from tropical and subtropical countries to temperate zone countries due to climatic change. In North Africa, unusually high rainfall is already showing more *Fusarium head blight* (FHB) outbreaks. The Indian sub-continent is currently spared from rains, and FHB appears during the wheat-growing season. If 'sporadic' rains occur more frequently with climate change, mycotoxin contamination of FHB may cause a huge problem for public health (food) and industry (feed). Citrus greening disease caused by *Diaphorina citri* kuwayama (Homoptera: Pyridae) - The relocation of Asian citrus to tropical and subtropical countries by pyrido is taking a zone in medium zones due to climate change. In North Africa, unusually high rainfall already indicates the occurrence of more *Fusarium head blight* (FHB). The Indian subcontinent is currently spared by rain, and FHB appears during the wheat cultivation season. When climate change causes a lot of sporadic rain, mycotoxin contamination in FHB can cause major problems for public health and industry.

b) Concentration of CO₂

Changing CO₂ concentrations affect the development and growth of many fungal, bacterial, and viral pathogens. A strain of *Colletotrichum gloeosporioides* pathogen population and infection cycles increased at elevated CO₂ (Chakraborty & Datta 2003). Similarly, the incidence of rust, powdery mildew, stemphylium blight, anthracnose, and alternaria blight, has been increased in dense canopies of crop. Elevated CO₂ concentration influences the expression of downy mildew (*Perenospora manshurica*), wilt (*Fusarium virguliforme*), and brown disease spots (*Septoria glycines*) disease of soybean (Eastburn et al. 2010). The growth of conidia and germ tubes of *C. gloeosporioides* fungi is less at higher CO₂ (700 ppm) concentrations, while the rate of sporulation was high at elevated CO₂ concentrations (Chakraborty et al. 2002). Lake & Wade (2009) noticed the aggressiveness of *Erysiphe cichoracearum* under elevated CO₂ concentration, along with leaf epidermal characteristics changes of plant. The increased CO₂ concentrations (780 ppm) shown to higher susceptibility of Remus wheat variety to *Fusarium head blight* and *Septoria tritici*. Overall, increased concentration of CO₂ on various plant diseases may be either positive or negative, and in majority cases it can be increased the disease severity (Zhou et al. 2017).

c) Moisture

Due to increased temperature, high rainfall and evapotranspiration increased more growth and dense canopy of plants that hold more moisture on leaf surface and make more conducive conditions for the growth and development of various soil-borne and foliar pathogens. Higher moisture conditions favour the development of late blight of potato and apple scab, whereas lower moisture conditions favour the development of powdery disease (Coakley et al. 1999). Potato (*Phytophthora infestans*) occurs at high temperatures (26.8 °C) and high moisture conditions (Fry et al. 2013). Drought conditions also favor some fungal pathogens, such as dry root rot and powdery mildew of pulse crops due to changing moisture conditions (Gautam et al. 2013). *Armilaria* sp. causes infection in drought conditions, which is not normally pathogenic (Lonsdale & Gibbs 1996). Similarly, drought factor affects the severity of viruses (Clover et al. 1999). In pulse crops, *Sclerotium*, *Rhizoctonia*, and oomycete fungi under moisture conditions cause soil-borne diseases (Sharma et al. 2010). Maximum incidence of apple canker has been observed in higher rainfall conditions in summer compared to the rainy season (Sharma 2012).

Effect of climate on host plant resistance

The inherent ability of plants to resist pathogens is called resistance. One of the direct consequences of climate change in the pathogen-host relationship is the genetic resistance of plants to disease. Several studies on climatic changes effect provide significant results on increased photosynthetic rates, accumulation of silicon, papillae growth, increased carbohydrate in leaves, more wax, excess epidermal cell layers, higher fiber, fewer nutrients, and increased resistance enzymes (Chakraborty et al. 2000; Osswald et al. 2006). The effects of climatic conditions increased the severity of pest and pathogen, which may also cause damage to plants (Johnson & Jones 2017). Paoletti & Lonardo (2001) observed the *Cupressus sempervirens*, a cypress clone resistant to canker caused by *Seiridium cardinale*, maintained its genetic resistance when cultivated in a high CO₂ environment. A number of pathogen cycles, faster development of colonies, and increased fecundity of pathogens and the occurrence of epidemics are directly influenced by increased CO₂ concentration and changed microclimate (Chakraborty et al. 2000). Similarly, in tomato plants, reduced stomatal aperture and increased disease resistance were observed under increased CO₂ concentration against *Pseudomonas syringae* pv. tomato DC3000 (Pst) (Li et al. 2014). St Clair (2010) described that the partial quantitative resistance confers resistance against pathogens by quantitative trait loci (QTL). FU (2009) reported that in wheat, the kinase START domain, Yr36, showed moderate resistance to various *Puccinia striiformis* races at 35°C °C temperatures but not confer resistance at temperatures below 20°C. Similarly, Plants carrying the Sr13 gene prompted transcription of resistance to *P. striiformis* in high temperatures (Zhang 2017). In viral diseases, RNA interference (RNAi) is shown to affect many viruses

(Ding 2010), but climatic factors temperature, affect RNAi mechanism in plants. Szitty et al. (2003) showed that RNAi viral defense mechanisms were less at low temperatures 15 °C in *N. benthamiana* against *C. ring spot virus* (CymRSV) compared to 27 °C. Similarly, cassava mosaic virus disease symptoms and titre concentration of virus are higher at 25 °C compared to 30 °C temperature. All these studies indicate that antiviral defense mechanisms are altered due to the impact of climatic factors. Various rust resistance genes, Pg3 and Pg4 of oat stem and Lr210 and Lr217 of wheat leaf, are sensitive and influenced by temperature (Das et al. 2016). The pathogens *Burkholderia glumea*, *A. avenae*, and *R. solanacearum* become more infective and break host resistance due to higher temperatures (Ahanger et al. 2013). Race of *Pst* 78S84 broke the resistance of Yr9 and Yr27 in PBW 343 in North Western India due to high temperature. The Xa7 is a blight resistance gene found effective against *Xanthomonas oryzae* pv. *oryzae*, at high temperature compared to other resistance genes (Webb et al. 2010).

Hosts show defense mechanisms (resistance) against various pathogens through the ABA, ethylene (ET), salicylic Acid, jasmonic acid, and hormones. ABA stress hormones are involved in regulating salinity, drought, and cold stress in plants (Vishwakarma 2017), whereas SA (Yan & Dong 2014), JA (Zhang et al. 2017), and ET (Glazebrook 2005) are involved against pathogens. Due to changed weather conditions, disease may be regulated through defense hormones. During the infection of *P. syringae*, increased concentrations of ABA and SA were observed (De et al. 2007). When the level of ABA increased, plants showed resistance to *P. syringae* and *Botrytis cinerea* (De et al. 2007). Similarly, effector-triggered Immunity (ETI) is genetically controlled by the plant pathogens. In tobacco, the N protein is found effective against *Tobacco mosaic virus* (TMV), while tomato Cf proteins against *C. fulvum* and R proteins against *P. syringae* at a temperature of 30 °C, but not effective at ETI greater than 30 °C. All these studies suggested that changes in climate conditions directly or indirectly altered the resistance mechanism of the host.

Effect of climate on biocontrol agents

Climatic variation altered the activity and potential of biocontrol agents. Changed climatic factors impact the structure and populations of antagonistic microbial groups in the rhizosphere and phyllosphere. Modification in soil nutrient availability, soil temperature, and soil water content drastically changes the biocontrol activities. It can be expected that environmental conditions associated with climate change will affect these communities. Bacterial endophytic populations, which colonize plant internal tissues such as roots, stems, shoots, leaves, as well as flowers, fruits, and seeds, may be affected by the climatic conditions (Hallmann 2001; Compant et al. 2010). Haase et al. (2007) observed that elevated CO₂ concentration reduced the nitrogen uptake capacity of many *Rhizobium* bacteria, which led to nitrogen

deficiency symptoms in plants; moreover, elevated CO₂ enhanced plant–plant–microbial nutrient race in soil rhizosphere. Sanders et al. (1998) showed increased rhizosphere growth in the of *Prunella vulgaris* compared to ambient CO₂ (350 µl⁻¹). Drigo et al. (2009) showed the effect of CO₂ on *Pseudomonas* and *Burkholderia* spp. but it was not affected *Actinomycetes* and *Bacillus* bacteria. Similarly, Kohler et al. (2009) reported increased plant growth due to *Pseudomonas mendocina* strains under increased CO₂ conditions. *Mycobacterium* spp. 44, *Pseudomonas fluorescens* and *Pantoea-agglomerans* increased the growth of winter wheat root and shoots at 16°C, compared to loamy sandy soil at 26°C (Egamberdiyeva & Hoflich 2003). *Trichoderma* spores germination and growth (Magan 1988), mycelium interactions with other fungi (Badham 1991), and release of enzymes (Grajek & Gervais 1987), are altered by high moisture conditions. Zehra et al. (2017) *Trichoderma* spp. used under various environmental conditions such as salt, temperature, pH, etc., against *Alternaria alternata*, *F. oxysporum* showed high potential. Similarly, the biocontrol agent of grey molds (*Botrytis cinerea*) in greenhouse cucumber plants is influenced by climate. The inhibition of grey morphology by the organic regulator *Trichoderma harzianum* T39 is more pronounced at higher temperatures and lower RH values (Elad et al. 1993; Chaudhari et al. 2023). Temperature can also alter the structure of the AMF network and induce more vesicle switches to the broader mycorrhizal mycelium network in warmer soil (Hawkes et al. 2008).

Effect of climate on biological control

Biological control of pests is one of the most important factors in integrated pest management, protecting ecosystems. Natural enemies of crops, such as predators, parasitic wasps, and pathogens, are affected by the effects of various abiotic components. The natural enemies of insect pests are sensitive to extreme climate factors such as heat, cold, wind, and rain. Due to climate change, the incidence of insect pathogenic fungi is favored by longer moisture conditions and may be stubbornly reduced by dry conditions (Newton et al. 2011). Natural enemies and host insect populations may respond differently to changes in climate. Hosts may pass through vulnerable life stages more quickly at higher temperatures, reducing the window of opportunity for parasitism, which may give great setbacks to the survival and multiplication of parasitoids (Gutierrez 2008; Petzoldt & Seaman 2010). Plants growing under elevated temperature and CO₂ concentration will provide different nutritional resources for invertebrate hosts which indirectly affect the fitness of predators and parasitoids feeding on these hosts and will also decline quality of their herbivore hosts (Wang et al. 2007). Chen et al. (2005) observed that the coccinellid predator, *Leis axyridis* Pallas (Coleoptera: Coccinellidae), of an aphid herbivore consumed more prey under conditions of higher CO₂ concentration. *Manihot esculenta* Crantz, parasitism of mealybugs is reduced under water and drought stress conditions in cassava (Calatayud et al.

2002). Rezacova et al. (2005) observed that *Chlonostachys rosea*, a biological control agent of *Botrytis* and other pathogens, and *Metarrhizium anisopliae*, an entomopathogen for insect pest control, were strongly associated with the cover crop in a high-CO₂ environment. Many beneficial enemies use chemical products produce by plants to locate their prey under elevated levels of CO₂ and higher temperatures (Stiling et al. 2002). Under increased temperatures, these chemical compounds present in oil helped find prey aphid (*Myzus persicae*) for *Diaeretiella rapae* parasitoids. Rundle et al. (2004) reported that the size of *Trichogramma carverae* decreased after exposure to 10°C or below in the early pupal stage. Similarly, adult parasitoid scelionid *Telenomus podisi* fecundity was reduced up to 80% (Bayram et al. 2005), while *Anagyrus ananatis* (Hymenoptera: Encyrtidae) produced only male generation (Pandey and Johnson, 2005). The *Wolbachia* bacteria parthenogenesis can be removed by high temperature exposure (Hurst et al. 2001). *Harmonia axyridis* (Pallis) (Coleoptera: Coccinellidae) a predator, has high flight capacity (Roy et al. 2016), but declined populations under hot and dry conditions (Grez et al. 2017). Jeffries et al. (2013) observed the long-distance dispersal of the lady beetle, *Coccinella septempunctata* (L.), and concluded a positive influence of high temperature coupled with low humidity. Similarly, Stijn et al. (2017) showed that diamondback moth *Plutella xylostella* (L.) negligible effect of high temperature compared to *Diadegma semiclausum* (Hellen). The *Menochilus sexmaculatus* population was also influenced due to increased temperature in Japan (Yamazaki 2017). Accordingly, Reddy et al. (2019) compared *Neochetina Eichhorniae* Warner, a biocontrol agent of *Eichhornia crassipes* (Mart.) Solms and found variation of cold temperature among populations. Augustinus et al. (2020) observed the influence of climatic factors on the population of *Ophraella communa* Lesage biocontrol agent of *A. artemisiifolia*. Similarly, Lu et al. (2017) showed a warming effect on *Agasicles hygrophila* Selman, a biocontrol agent of *A. philoxeroides* (Mart.) Griseb. All these findings indicated alteration of the biological control of different insect pests, pathogens, and weeds due to weather conditions.

Effect of climate on interspecific relationships

Climate change can affect several aspects of host plant biology, including its phenology, sugar and starch, nitrogen and phenol content, roots and photographic biomass, number and size of leaves, amount and composition of leaf wax, changes in stomatal density, and conductivity and conductivity. Any alteration in these activities may affect the infection and root decay by pathogens (Colhoun 1973), which also directly influences the relationship of pathogens (Gessler et al. 2011). Brosi et al. (2011) reported the effect of increased or decreased CO₂ concentrations in high temperatures, which may affect the beneficial bacteria and plant interactions in *Lolium arundinaceum* and *Neotyphodium coenophialum*. In other contexts, VAM mycorrhizae fixed carbon in plants to fungi, but it shows increased CO₂ effect on their associations (Fitter

et al., 2000). Drigo et al. (2010) suggested a positive increased atmospheric CO₂ effect on plant and beneficial microbial associations. Caffarra et al. (2012) combined detailed phenological models of grapevine with phenological models of grape powdery mildew and the European grapevine moth, which changes the interactions between these species. The elevated CO₂ and temperature changes the plant and soil microbial sense and response also (Chakraborty et al. 2012) and influences the plant pathogen association (Ferrocino et al. 2013). The increased CO₂ level influenced the number of leaves, branches, leaf area, leaf area per plant, plant height, and crop yield (Eastburn et al 2011). McElrone et al. (2005) found a positive effect of increased CO₂ level on *Phyllosticta minima* severity due to host metabolism changes. The increased CO₂ altered stomata opening and leaf metabolism, resulting in decreased leaf infection of stomata entering pathogen (McElrone et al. 2005). Temperature plays a potent role in the development of plants and plant-pathogen interactions. Temperature is essential for the growth of plants as well as pathogens and affects the penetration, survival, development, reproduction rate, and dispersal of many pathogens. The high temperature increased the susceptibility in some resistant varieties, but others showed resistance against pathogenic fungi (Coakley et al. 1999).

Effect of climate on pest adaptations

Climate change lies in adaptive landscapes. Adaptive environments are conceptual frameworks in which organismal fitness is presented as a function of phenotype at a particular geographic location. If the pre-climate change population moves to a lower fitness during climate change, fitness decreases. Local adaptation allows climate change to replace population sizes near the edge of species domains (Pelini et al. 2010). The direct effects of changing temperature are not the only factors affecting the adaptive landscape of an organism. Indirect interactions among the organism's affected by climate change (Urban et al. 2012). *Magnaporthe grisea* is prevalent in Brazil and have high adaption in all the wheat growing areas due to changed weather conditions. Similarly, spot blotch (*Cohliobolus sativus*) is present in Southern Brazil, Bolivia, Paraguay, and Eastern India. Due to the adaptation of this pathogen in warm conditions, more than 50 % wheat areas affected in South Asia under favorable conditions. Due to changed weather conditions, the wheat grain filling speed and spot blotch severity has been increased in India, Nepal, and Bangladesh from last 6 years. Yellow rust (*Puccinia striiformis*) is present in cool wheat-growing areas of North America, western China, Northern Europe, the Middle East, and Central Asia. Changing climatic conditions indicate that new epidemics may appear due to changes in the races of rust and existing races becoming more tolerant to heat. Similarly, the *Indian Peanut Clump Virus* is restricted to a few areas (Rajasthan, southern India) where wheat is grown on peanut fields. Climate changes are likely to affect the cropping systems' patterns. Changes in crop rotations due to high cereal prices may induce a threat of the

infection and spread of disease. Lyon & Broders (2017) showed the positive effect of temperature on spore germination, infection, and survival of *Pst*. However, *Pst* prefers temperatures between 7 and 12 °C (Chen et al. 2014). Similarly, temperature range adaptation is also reported in isolates (Sharma-Poudyal et al. 2014). The warrior race of *Pst* that invaded North Western Europe in 2011 showed wider adaptation to a range of temperatures due to warm (Spain) and cold (Sweden) areas (Hovmoller et al. 2016). Similarly, Mariette et al. (2016a) found thermal adaptation in *P. infestans* in various climatic zones.

Effect of climate on the efficacy of pesticides

Temperature changes may alter pesticide residue presence in foliage, and the quality of products can be changed. Enriched CO₂ concentrations and temperature and altered plant morphology can affect the translocation, penetration, and action of systemic pesticides. Besides, changes in plant growth can be alter the higher susceptibility period to diseases, which leads to new calendar for fungicide sprays (Pritchard & Amthor 2005). The pesticide application per acre influenced the cost of corn, potatoes, cotton, soybeans, and wheat. Similarly, cost of corn, soybean, cotton, and potatoes also increases due to high temperature, while same has been decreased for wheat. Higher temperature and CO₂ support the crops vegetative growth also (Gutierrez et al. 2008), which decreased pesticide residue in plants. It is accompanied by reduced pesticide uptake by the roots from the upper soil layer as they penetrate deeper soil layers. Temperature increase, reduced rainfall, and high concentrations of atmospheric CO₂ can develop fungicide resistance in pathogens, resulting in an increased number of fungicide applications (Delcour et al., 2015). Fungicide uptake and translocation in plants are influenced by precipitation and will be limited under dry conditions due to a reduced rate of transpiration (Keikothaile 2011). The concentration of pesticides and degradation will be induced due to high volatilization rate, water, temperature, and exposure to sunlight. A pesticide is also influenced by wind, sun radiation, and rainfall (Steurbaut 2009; Keikothaile 2011) that affect the pesticide transport, degradation, pesticide availability and efficacy. Systemic fungicides could be affected negatively by physiological changes that slow uptake rates, such as smaller stomatal openings or thicker epicuticular waxes in crop plants grown under higher temperatures. These same fungicides could be affected positively by increased plant metabolic rates that could increase fungicide uptake. A humid soil after rainfall favors pesticide volatilization (Navarro et al. 2007). Chen & McCarl (2001) examined the effects of climate change on pesticide expenditures, finding that pesticide expenditures rise with increased temperatures and precipitation for the majority of crops. Similarly, Shakhramanyan, Schneider, & McCarl (2013) indicate climate change induced increases in pesticide usage and that this in turn raises external environmental and health costs. Hence, variability in climatic factors influences the efficacy of pesticides.

Conclusion

The impact of climate variables has limited research studies on plant diseases and their management. Now, the emphasis must shift from the assessment of climatic variables to the development of mitigation management strategies. There is an urgent need to develop different climate-based forecasting models for the prediction of disease distribution and migration, develop new unbreakable resistant cultivars, and evaluate the efficacy of chemical, physical, and biological control tactics in different climatic conditions. Research should be focussed according to future climatic scenarios with the aim to develop new artificial intelligence-based (AI) tools, models, and tactics. Trials on the effect of climatic factors below and above ground level on natural enemies, bioagents, inter-specific relationship of pathogens, pest adaptation, and efficacy of pesticides should be carried out to understand their effects along with how plant diseases affect.

Funding sources

This research received no specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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