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Review Article

Prospects of climate change effects on crop diseases with particular reference to wheat

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Abstract

Global climate change has considerably threatened wheat production. Rising global temperature is likely to affect wheat productivity directly or indirectly by shifting the dynamics of various abiotic and biotic factors. Shifting diseases and virulence patterns of plant pathogens is assumed to be a significant event for meeting the global food demand in the future, which in turn is expected to make future modifications in disease resistance breeding. Increasing population, industrialization, burning of fossil fuels, and other human activities are going to cause climatic variations. There would be an increased carbon dioxide (CO_2)/ greenhouse gas emissions, temperature, erratic rainfall, and other issues which will have a direct impact on crop production as well as disease and pest situations. In general, the incidence of damping-off, powdery mildew, stem rust, leaf rust, Karnal bunt, Fusarium head blight, and blast on wheat will more likely increase. Stripe rust incidence may decrease on wheat. However, isolates of *Puccinia striiformis tritici* that are adapted to relatively higher temperatures have been observed since 2000 in many countries. From plant disease management perspective, a precise understanding of a particular disease at field level is required, so that the probable effects of different abiotic and biotic factors under climate change situations could be assessed and estimated comprehensibly. Experts working in different areas of agriculture would have to work through a system approach and prioritize the effects of climate change in a broader context, comprising the entire agro-ecosystem. The current article presents the current status of climate changes in relation to the changing wheat disease spectrum and their management strategies.

Keywords: Global warming, wheat, diseases, disease prediction and management

1. Introduction

Climate change is described as the changes in the usual climate with respect to abiotic (temperature, precipitation, wind, and others) and biotic elements that result from various human activities including burning of fossil fuel, deforestation, industrialization, exploitation of natural resources, and others. Such activities increased with the expansion of the industrial revolution after the eighteenth century. The ambient concentration of greenhouse gases (GHGs) including carbon dioxide (CO_2) has increased significantly for more than 650 thousand years (Mohammed *et al.*, 2021; Siegenthaler *et al.*, 2005). Since the year 2000, the concentration of CO_2 is increasing at a much higher rate than in previous decades (Canadell *et al.*, 2007). Same is the case with other GHGs like methane

(CH_4), nitrous oxide (N_2O), ozone (O_3), and others (Song *et al.*, 2014; Spahni *et al.*, 2005). The ambient global temperature on earth was also reported to increase at the rate of 0.2°C per decade during the last few decades (Smith *et al.*, 2015; Hansen *et al.*, 2006), while the mean annual global temperature has increased by 1.0^{0}C since 1881 (IPCC 2019). Changes in the water cycle in the form of erratic rainfall have also been observed. Fluctuations in climate are supposed to occur despite stabilization in GHGs concentrations, due to the thermal inertia of the system and also due to the necessity of an extended time period for the system to achieve a lower equilibrium.

World agriculture is projected to face a significant decline as a consequence of climate change unless and until a substantial reduction in the emissions of GHGs is achieved. As a consequence of global warming, the global agricultural productivity is estimated to drop down from the levels that were otherwise expected to increase by about 3 to 16 percent by 2080s (Cline 2007). Plant diseases, responsible for causing a minimum loss of 10% of global food production, are considered as a major limiting factor in achieving global food security (Strange and Scott, 2005). The role of the different biotic and abiotic environmental factors in the development of a specific plant disease is an acknowledged well-known fact for over a thousand years. These factors can also affect host (growth and resistance), pathogen (reproduction, dispersal, survival and pathogenicity), and their interaction. The dependency of plant diseases on several environmental factors advocates that climate change will force alterations in the current phyto-sanitary setup. Climate change may have positive, neutral, or negative effects on disease development in a specific host plant or region (Ghini *et al.*, 2008). Therefore, the understanding of such effects becomes crucial for implementing improved disease management strategies including disease resistance breeding in plants and thereby avoiding more yield losses (Ghini *et al.*, 2008).

Global warming is one of the serious threats to wheat production mainly in the areas which are vulnerable to soaring air temperature together with reduced rainfall (Wang *et al.*, 2018). Changing climate is expected to influence several abiotic and biotic stresses on wheat. Among the biotic stresses, wheat diseases including rusts, blast, spot blotch, and powdery mildew are the most important limiting factors in achieving the projected target of wheat production in future (Prasad *et al.*, 2020a), and are assumed to be influenced by changing climate variables (Pandey *et al.,* 2019). The occurrence and distribution of these diseases might witness a drastic shift in future due to the direct effect of climate change or indirectly through climate change influence of different abiotic and biotic factors. A simulation study, conducted to predict the effect of climate change on wheat productivity in north-western India, revealed that the rising temperature together with water scarcity will have highly adverse effects on wheat quality, production, and productivity in future and that too under the positive effect of other factors including elevated CO_2 concentration (Kumar *et al.,* 2021; Tripathy *et al.,* 2020; Zaveri and Lobell 2019). In contrast, the increasing temperature would favor wheat production in the regions, where wheat production is not feasible as of now due to a prevailing lower temperature than required for wheat production (Tao *et al.,* 2014). Thus, the estimated climate change effects may be reduced through the sharing of gene pools amongst wheat breeding programs in such situations (Shew *et al.,* 2020). However, temperature rise will also result in early terminal heat, early maturity of wheat that will ultimately cause a yield penalty (Pandey *et al.,* 2019; Singh *et al.,* 2019).

Predicting the probable impact of climate change on global wheat production is extremely complex and challenging due to poor understanding of the interactions among various abiotic factors including temperature, precipitation, ambient concentration of different atmospheric gases such as CO_2, O_3, and others (Asseng *et al.,* 2015). Overall, the future wheat yield forecasts primarily will rely on the use of different wheat yield simulation models, climate change prediction models, emission scenarios, etc. (Ceglar and Kajfez-Bogataj, 2012).

Climate change and crop pests

Besides influencing the crops, the climatic factors also affect their associated pests. The growth, survival, distribution, and multiplication of crop pests are significantly determined by environmental factors. Similarly, pest management strategies including chemical management are also affected by different climatic situations together with the crop type and extent of pest damage or loss. Moreover, the amount, frequency, and timing of rainfall is another important factor that has a direct association with pesticide efficacy, tenacity, and transport. A number of investigations have speculated that the crop pests would become more active and could cause more damage than now under climate change situations, and therefore, could pose a serious threat of monetary loss to growers and global food insecurity (Shew *et al.,* 2020; Coakley *et al.*, 1999).

2. Climate change vis-a-vis crop diseases

Although, substantial success has been accomplished in the management of plant diseases with technological and scientific advancement, yet plant diseases are still posing significant challenges to global crop production. Plant diseases might further impact the range of cultivated crops/cultivars in a specific region based on their adaptability to the changing environmental factors. Some evidences strongly suggest that changing environmental factors such as precipitation, temperature, composition of atmospheric gases etc., would lead to a complex interface among scientific, social, technological, and economic events for plant diseases (Jeger *et al.,* 2021). It is hypothesized that changes in environmental factors possibly will have an insignificant influence on the occurrence of diseases unlike their effect on crop management practices and genetic improvements in wheat (Asseng *et al.,* 2013), potato (Fleisher *et al.,* 2017) rice (Li *et al.,* 2015) and maize (Bassu *et al.,* 2014). The growth, multiplication, pathogenesis, spread, and survival (overwintering or oversummering) of plant pathogens are influenced by several environmental factors comprising temperature, relative humidity, rainfall, photoperiod, wind direction and speed, and other extreme events (Fig 1). Of these, relative humidity, ambient temperature, and precipitation have maximum impact on the outcome of a specific host-pathogen interaction, spread, and survival of pathogens. For instance, moist soil encourages the germination, growth, development, and infectious nature of fungal and bacterial propagules and affects the movement and growth stages of plant pathogenic nematodes (Prank *et al.,* 2019). Conversely, some pathogens thrive poorly under deprived aridity; and some pathogens like *Blumeria graminis tritici* causing powdery mildew in wheat grow well in warm and dry conditions provided the availability of sufficient dew during the night (Te Beest *et al.,* 2008). Predicting the probable effects of climate change on the host, pathogen, their interaction, population dynamics, community structure in agro-ecosystem, and micro-evolutionary developments, etc. is a prerequisite to envisage the effects of changing climate on specific crop disease.

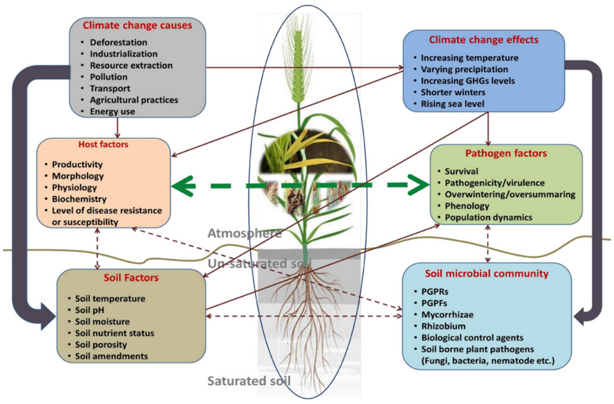

Figure 1. Potential direct and indirect effects of climate change on wheat, its pathogens and their interactions.

The estimation of future losses due to plant diseases under climate change situation would be possible only after analyzing a large number of inter-related abiotic and biotic factors, which will have direct and indirect impacts on plant pathogens and diseases caused by them. A higher CO_2 level is assumed to amend the precipitation and penetration of light through the plant canopy, which will have direct effect on canopy structure and microclimate environment (Sikma *et al.,* 2020). The altered canopy structure and microclimate will change host physiology as well as morphology and therefore, disease epidemiology. We may witness a reduction in plant canopy post-infection by some pathogens even under double ambient CO_2 levels. For instance, as an adaptation of photosynthesis, under increased CO_2 level and powdery mildew disease influenced dropping down in photosynthesis rate, hindered plant growth in barley at higher CO_2 levels is reported (Hibberd *et al.*, 1996). Reduction in growth of diseased plants is observed frequently even if disease severity is reduced under increased CO_2 levels (Chakraborty *et al.*, 1998). For instance, the growth of *Maravalia cryptostegiae*, a fungal biological control agent that causes rust in woody weed rubber vine (*Cryptostegia grandiflora*), is reduced under elevated CO_2 concentration twice to the ambient (Kaukoranta, 1996). A 3-year long controlled environment simulation study was conducted to study the effect of rising temperature on potato yield (Kaukoranta, 1996). The finding of that study has advocated that with 1 to 3°C warming, proficiency of chemical control of potato late blight would extend by 10-20 days per 1°C increase in temperature, and that the extent of yield loss in unprotected potato crops would be of the equal magnitude as the improvement in yield potential, which they estimated about 2 t/ha of dry matter per 1°C temperature increase (Kaukoranta, 1996). The implications of such studies on yield parameters cannot be fully followed unless some field experimentation is conducted, yet these findings suggest that CO_2 levels and improved water use efficiency-related estimation of crop harvest may not be convincing (Asseng *et al.,* 2015).

The indirect effects of environmental factors such as ozone layer transmitted ultraviolet rays (UV-B) may predispose crop plants to a number of plant diseases, which might result in higher yield losses than that caused by a specific disease alone (Manning and Tiedemann, 1995). However, the effects of UV-B are not consistent on plants and their pathogens. Higher disease severity as influenced by changed climate might not constantly result in increased yield losses (Luo *et al.*, 1995). In a comprehensive review on the effect of climate change on plant diseases, Chakraborty *et al.* (1998) listed the probable effect of elevated CO_2 on diseases caused by 10 biotrophic and 15 necrotrophic pathogens. Enhanced disease severity under elevated CO_2 levels was reported in six biotrophic and nine necrotrophic pathogens, while disease severity was reduced in four biotrophic and necrotrophic pathogens each (Chakraborty *et al.*, 1998). Inclusive analysis of potential climate change effects through altered disease severity on yield losses is currently unavailable. Certain assessments of monetary loss or gain due to changed climate effects on diseases of some major crops have been made (Bevitori and Ghini 2014; von Tiedemann, 1996). For example, the effects of climate change on blast disease in rice have been predicted by simulating the changes in temperature and precipitation in five Asian rice-growing countries (Bevitori and Ghini 2014; Luo *et al.*, 1995). There was considerable effect of temperature changes on rice blast severity, whereas rainfall had an insignificant effect on disease in a majority of the locations. However, these effects were inconsistent among different agro-ecological zones. This study also predicted that the future risk of rice blast would be high in currently cooler, subtropical rice-growing zones, for example, Japan; whereas, in the humid tropics and subtropical countries like the Philippines rice blast severity would reduce substantially with rising temperature.

2.1 Shift in infectious plant diseases

Changed climate might modify the structure and dynamics of microbial communities thriving in soil or air to manipulate plant growth and development (Cavicchioli *et al.,* 2019). Altered composition and dynamics of phyllosphere and rhizosphere may affect dynamics of plant pathogens and diseases caused by them under the influence of related microbes with bio-control activities (Fig 1). The soil environment is not likely to be influenced by rising CO_2 levels in the atmosphere since soil microbes are frequently exposed to the CO_2 level that is up to 15 times more than the ambient CO_2 levels in the atmosphere. The establishment of microbes like arbuscular mycorrhizal fungi (AMF) is favored by the plantation of trees in soils with poor nutrient status (Cavicchioli *et al.,* 2019; Klironomos *et al.*, 1997). However, there are contradictory reports on how the soil colonization by AMF is favored by fluctuations in the CO_2 levels and plant and soil nutrient status (Cotton 2018). The AMF could have a positive, negative, or neutral influence on the occurrence of particular plant disease; however, the findings to suggest their conclusive role are poorly documented despite much experimentation in the area (Roger *et al.,* 2013; Pfleger and Linderman, 1994). Accordingly, the understanding of the probable effect of mycorrhizae on the incidence of plant diseases under changed climate needs additional research. The increased CO_2 level in the soil can also influence the effects triggered by other elements for instance nutrient status, nitrogen in particular and water availability. Interaction of these factors and their effect on wheat powdery mildew, caused by *Erysiphe graminis*, was studied by Thompson *et al.* (1993) in England. They found decreased percent shoot nitrogen contents under enhanced CO_2 concentration which resulted in reduced powdery mildew disease. Thompson and Drake (1994) evaluated the effect of water and nitrogen contents on infestation by insects and fungal disease severity in C3 and C4 plants. In elevated concentrations of atmospheric CO_2, there was a significant reduction in shoot nitrogen content and 37% reduction in fungal infection on *Scirpus olneyi* Grey (C3) plants. Whereas, *Spartina patens* (Ait.) Mobl. (C4) plants had unchanged nitrogen (N) concentration and increased severity of fungal infection under elevated CO_2 concentrations. Further to the effect of N and irrigation, the outcome of higher CO_2 levels could also be influenced by the fluctuating concentration of other gases. For instance, wheat leaf rust (*Puccinia triticina*) was strongly inhibited by an increased level of ozone, but largely unaffected by elevated CO_2 (von Tiedemann and Firsching, 2000).

It is expected that changed climate would largely result in a poleward shift of the agro-climatic zones, and corresponding crops that are cultivated in these zones along with the related phytopathogens. Carter *et al.* (1996) projected that under changed climate, maize would be able to grow unfailingly by the year 2050 in southern Finland and outspread further north. Similarly, the potato late blight threat would rise in all potato growing regions while potato diseases caused by nematodes might turn into a problematic issue with an increased number of disease cycles per crop season. Parallel estimates have been made for oak decline disease in oak caused by *Phytophthora cinnamomi.* These predictions suggest that oak decline pathogen would move further north and the disease severity would increase across all the regions including the native environment of the pathogen (Brasier and Scott, 1994). The migration path of these pathogens would follow the distribution pattern of their hosts, while pathogens establishment, survival, and dispersal would largely depend on the physiology of their host and involvement of different biotic and abiotic factors in the new ecosystem/environment (Fig 1).

Most of the aggressive plant pathogens, infecting a range of crop plants, including *Fusarium* spp., *Rhizoctonia* spp., *Sclerotium* spp., *Phytophthora* spp., *Sclerotinia* spp., and many other necrotrophs may move from cultivated crops to wild plant communities (Kodati *et al.,* 2021). Necrotrophs and other plant pathogens with a wide host range might destroy the migrating crops by introducing new diseases. Likewise, less aggressive pathogens might destroy crops grown as monocultures in the nearby vicinity of natural plant communities. There are several well-documented cases where indigenous pathogens have been reported to cause new diseases in introduced crop plants, growing in the vicinity of other indigenous hosts (Keesing *et al.,* 2010; Jones and Baker, 2007). Two best examples that prove this statement include fire blight disease of apple and pear caused by *Erwinia amylovora* in USA and coffee rust caused by *Hemileia vastatrix* in Asia. *E. amylovora* was known to be a minor disease on native members of family Rosaceae in the USA. But the introduction of pears and apples by European migrants in some regions of USA resulted in severe devastation of these plants due to fire blight disease caused by *E. amylovora.* Likewise, the introduction of highly susceptible coffee species (*Coffea arabica*) in Asia during the late 1800s resulted in a severe coffee rust epidemic in the region, before that the coffee rust pathogen was surviving on some alternate hosts in the forests near to coffee estates (Carefoot and Sprott, 1967).

2.2 Plant disease management under changing climate

Because of poor understanding of the impacts of climate change on crop plants or the microbes causing diseases in them, forecasting the possible consequences of disease management practices with any assurance is not feasible till date, though, it is likely that the changed climate would essentially impact the degree of host resistance, pathogenicity in the pathogen and/or efficacy of pesticides and other bio-agents. Intensive investigations are therefore, desired to find out the circumstances where the efficiency of disease management strategies might get hampered due to changed climate. The efficiency of host resistance to diseases might increase considering improved static and dynamic defence mechanisms subsequent to changes in host's morphology, physiology, including nutrient content and availability of water in the soil. However, there are exceptions for instance a number of rust resistance genes may become less effective at warmer temperatures prevailing under the changed climate. However, most of the disease prediction models studied so far are influenced by several biotic and abiotic elements affecting host, pathogen, and their interaction, and the type of disease prediction models used (Fenu and Malloci, 2021). Hence, drawing conclusions solely based on few simulation studies would be inconclusive for breeders to breed for resistance to specific plant disease. Altered genetic resistance of host plants to their pathogens is one of the most significant concerns of climate change effects on different host-pathogen interactions. Changed climate altered host morphology, and physiology has a direct connection with the expression of disease resistance, which could be modified for the benefit of crop plants by applying both traditional and genetic engineering breeding tools. There are indications of structural as well as physiological alterations in plants under changed climate conditions. A substantial rise in the degree of photosynthesis, production of papillae, formation of epidermal layers, accumulation of wax, a higher concentration of silicon at the site of infection, increased fiber content, rise in carbohydrate amount in leaves, a decline in nutrient content, and shift in the synthesis of enzymes responsible for controlling resistance mechanisms, etc. resulting from climate change effects are reported in different host-pathogen interactions (Chakraborty *et al.*, 2000).

The effect of rising CO_2 levels on the magnitude of genetic resistance in host plants has been proved in several studies (Zhou *et al.,* 2017; Paoletti and Lonardo, 2001; Chakraborty *et al.*, 2000). The effect of elevated CO_2 concentration on resistance of a cypress (*Cupressus sempervirens*) clone remained ineffective to canker disease caused by *Seiridium cardinal.* Additionally, the effect of rising temperature and other abiotic factors on the magnitude of genetic resistance by host plants has also been explored. Such effects vary depending on the type of resistance. Several modifications in host morphology, and physiology could possibly amplify the degree of host resistance. However, the biggest risk to the expression of genetic resistance is the modifications in pathogens habits, such as elevated CO_2 concentration may help pathogens to migrate, survive, and cause disease more efficiently and thus, overcome host resistance. The enhanced pathogenicity together with prolificacy of a particular pathogen and proliferating plant canopies fasten the rate of occurrence of plant disease epidemics under beneficial microclimate environment (Chakraborty *et al.*, 2000).

Despite all the above-discussed effects, the changed climate may also have an impact on the efficacy of chemical pesticides used for the management of different pests including plant pathogens, insects, and weeds. Such effects on the efficacy of pesticides could be the results of the following two possibilities: (i) variation in temperature and relative humidity might change the duration and availability of chemical pesticide residues present on plant canopy or in soil and (ii) the infiltration, transport and mode of action of systemic pesticides on and in the plant system are expected to be directly influenced by morphological or physiological characteristics of host plants under elevated temperature or CO_2 concentration. For instance, denser epicuticular wax and epidermal layers on plant stem or leaves (Wolfe, 1995) could slow down the uptake of the chemicals by the crop plants, and flourishing plant canopy might adversely disturb the spray coverage, thereby reducing the concentration of active ingredient in spray suspension on host tissues. Accordingly, disease management strategies including changes in the fungicide application calendar will need to be restructured to minimize crop losses.

Similarly, the pesticide market could face certain drastic changes under changed climate. The pesticides with higher efficacy, a novel mode of action, and higher adaptability to climate change events would be more in demand than their counterparts. The defectiveness and adaptability of some pesticides under fluctuating abiotic factors including precipitation and temperature were analyzed in several US locations using a regression model (Chen and McCarl, 2001). The study concluded that per acre average cost of pesticide increased in wheat, soybeans, cotton, potatoes, and corn with an increase in precipitation. Similar was the case in corn, cotton, soybean, and potatoes when the ambient temperature was increased, however, per acre average cost of pesticide decreased in wheat with increase in temperature. Another aspect that would affect the pesticide market could be the rising awareness among people towards the value of anthropogenic actions in the course of resource exploitation by use of hazardous chemicals. People will unquestionably stress on the adoption of biologically safe non-chemical strategies of plant disease management.

There is no conclusive evidence to prove the influences of changing climate on the effectiveness of biological control of crop diseases. Few reports reveal the possible effect of climate change on the dynamics and structure of the microbes' populations in the rhizosphere and/or phyllosphere. Some crucial soil features such as water content, temperature, nutrient status etc. are expected to face certain alterations under changing climate, which will further influence the activity of microbes inhabiting the rhizosphere (Nosengo, 2003). The rising soil CO_2 concentration up to the tune of 600 ppm could not alter the microbial community; however, climate change effects on plant diversity could indirectly change population structure and dynamics of the microbial community in the soil (Gruter *et al.*, 2006). The elevated CO_2 concentration had a strong association with the population and efficiency of *Metarrhizium anisopliae*, a commonly known entomopathogenic fungus, and *Chlonostachys rosea*, biological control agent of a number of plant pathogens including *Botrytis* (Rezacova *et al.*, 2005). Such studies would be critical for sustaining the usefulness of biological control under changing climate. However, such forecasts are comparatively complicated and largely rely on the effect of several other abiotic and biotic factors that influence the efficiency of biological control. There are speculations that the efficiency of biological control would worsen considering the higher sensitivity of biological control agents towards the extreme weather conditions in the future (Garrett *et al.*, 2006). Conversely, there are arguments that biological control would be more in demand in the future, as increasing awareness in the society of harmful effects of chemical pesticides thereby adopting a more eco-friendly and sustainable ways of managing crop pests including plant pathogens (Lu *et al.,* 2015; Ghini *et al.*, 2008). For meeting such challenges, experts working in different areas of agriculture would have to work through a systematic approach and prioritize the effects of climate change in a broader context, comprising the entire agro-ecosystem.

2.3 Likely effect of climate change on wheat diseases

Wheat is prone to a number of fungal diseases including rusts {black/stem rust (*P. graminis tritici*), yellow/stripe rust (*P. striiformis tritici*) and brown/leaf rust (*P. triticina*)}, powdery mildew (*Blumeria graminis tritici*), tan spot (*Pyrenophora tritici-repentis*), leaf blotch (*Mycosphaerella graminicola*, *Phaeosphaeria nodorum*), spot blotch (*Cochliobolus sativus*), Fusarium head or ear blight (*Fusarium graminearum* and other *Fusarium* species) and more recently wheat blast (*Magnaporthe oryzae* pathotype *triticum*). Globally, a major proportion of wheat yield loss due to biotic stresses is caused by fungal pathogens as against bacterial, viral, or other wheat pests. In general, viral diseases in wheat are predicted to increase with a changing climate (Vassiliadis *et al.,* 2018; Tr bicki *et al.,* 2015). A shift in various climatic conditions including temperature, rainfall, level of CO_2, O_3, and other important gases in the atmosphere, soil factors etc. may influence the occurrence of wheat diseases. Changes in these factors may alter the level of interaction between the host and pathogen by changing or modifying the pathogens population dynamics, geographical distribution, synchronization in their life cycle events, and survival (West *et al.*, 2012). The significant influence of fluctuations in winter temperatures on the occurrence of yellow rust and powdery mildew on wheat has been determined (Jevtić *et al.,* 2020). There was a significant influence of wheat genotypes and climatic elements on the interactions among obligate pathogens and the predominance of one pathogen over another (Jevtić *et al.,* 2020).

There are evidences that suggest the direct positive or negative interaction between climate change and the occurrence of wheat diseases; however such information is not compiled comprehensively. Recently, there was a slow but steady increase in a number of studies published, which speculated the probable occurrence of specific wheat diseases under the influence of changing climatic conditions in the future. Future occurrence of different wheat diseases including rusts (Chakraborty *et al.*, 2011), Karnal bunt (Dumalasova and Bartos. 2009), Septoria tritici leaf blotch (Gouache *et al.*, 2012), Fusarium foot rot (Pettitt and Parry, 1996), Fusarium head blight (Fernandes *et al.*, 2004; Madgwick *et al.*, 2011), and other wheat diseases (Kaur *et al.*, 2008), have been speculated for different agro-climatic zones of the world. A number of reports speculating the effect of climate change on wheat diseases are summarized in Table 1.

Table 1. Likely prediction of occurrence of wheat diseases under climate change scenario

Wheat disease (Pathogen)	Predicted effect on pathogen/disease	Prediction approach	References
Stripe rust *(Puccinia striiformis)*			
Germany	Decrease	Speculation*	von Tiedemann, 1996
North India	Decrease	Speculation	Kaur *et al.* 2008
United Kingdom	Decrease	Speculation	Chancellor and Kubiriba, 2006
Brown/leaf rust *(Puccinia triticina)*			
France	Increase	Simulation**	Caubel *et al.* 2017
Germany	Increase	Speculation	von Tiedemann, 1996
Luxembourg	Increase	Simulation	Junk *et al.* 2016

Canada (Ontario)	Decrease	Speculation	Boland *et al*. 2004
North India	Increase	Speculation	Kaur *et al*. 2008
France	Decrease	Simulation	Gouache *et al*. 2011
Stem rust *(Puccinia graminis)*			
Canada (Ontario)	Decrease	Speculation	Boland *et al*. 2004
North India	Increase	Speculation	Kaur *et al*. 2008
United Kingdom	Sporadic	Speculation	West *et al*. 2012
Spot blotch *(Cochliobolus sativus)*			
South Asia	Increase	Speculation	Sharma *et al*. 2007
North India	Increase	Speculation	Kaur *et al*. 2008
United Kingdom	Increase	Speculation	West *et al*. 2012
Septoria tritici leaf blotch *(Mycosphaerella graminicola)*			
Germany	Increase	Speculation	von Tiedemann, 1996
Canada (Ontario)	Decrease	Speculation	Boland *et al*. 2004
United Kingdom	Decrease	Speculation	Chancellor and Kubiriba, 2006
France	Decrease	Simulation	Gouache *et al*. 2012
Septoria nodorum blotch *(Phaeosphaeria nodorum)*			
United Kingdom	Slight change	Speculation	West *et al*. 2012
Tan spot *(Pyrenophora tritici-repentis)*			
Canada (Ontario)	Decrease	Speculation	Boland *et al*. 2004
United Kingdom	Slight change	Speculation	West *et al*. 2012
Powdery mildew *(Blumeria graminis)*			
Finland	Increase	Speculation	Hakala *et al*. 2011
Sweden	Increase	Speculation	Roos *et al*. 2011
Stinking bunt *(Tilletia controversa)*			
Canada (Ontario)	Increase	Speculation	Boland *et al*. 2004
Tilletia indica *(Karnal bunt)*			
Europe	Increase	Simulation	Baker *et al*. 2000
United Kingdom	Increase	Speculation	West *et al*. 2012
Loose smut *(Ustilago tritici)*			
Canada (Ontario)	Increase	Speculation	Boland *et al*. 2004
Fusarium head/ear blight *(Fusarium species)*			
Sweden	Increase	Speculation	Roos *et al*. 2011
North India	Increase	Speculation	Kaur *et al*. 2008
United Kingdom	Increase	Speculation	West *et al*. 2012
Eyespot *(Oculimacula yallundae)*			
Germany	Decrease	Speculation	von Tiedemann, 1996
Finland	Increase	Speculation	Hakala *et al*. 2011
United Kingdom	Increase	Speculation	West *et al*. 2012
Take all disease *(Gaeumannomyces graminis)*			
Ontario, Canada	Decrease	Speculation	Boland *et al*. 2004

*Expert knowledge based speculations that consider the epidemiology of plant diseases

**Simulation are based on disease forecasting models

The incidence of different wheat diseases has been assumed to shift strongly in Punjab, India (Kaur *et al.*, 2008). Currently, yellow rust is one of the major yield-limiting factors in this region but with increasing temperature, its occurrence is anticipated to reduce in the future. However, the occurrence and prevalence of high-temperature tolerant isolates of *Puccinia striiformis tritici* may become predominant. Conversely, present-day minor diseases in the region including stem rust, foliar blights, brown rust, and Fusarium head blight are expected to upsurge in upcoming decades (Kaur *et al.*, 2008). Such speculations support the fact that changing climatic conditions may change the occurrence of different diseases in a region, and that presently minor diseases may threaten wheat production in the future (Duveiller *et al.*, 2007).

Generally, different abiotic factors like temperature, precipitation, photoperiod, and wind direction and velocity influence the disease causing potential of plant pathogens by affecting almost all the disease cycle events occurring during pathogenesis such as inoculum production and germination, and dispersal. The temperature is one of the most crucial factors that decide the outcome of a particular host-pathogen interaction. Prolonged higher temperature (beyond supra-optimal temperature) conditions will abbreviate incubation and latency period, which will increase the number of disease cycles per crop season and thereby more disease for polycyclic diseases like rusts (Wojtowicz *et al.*, 2017). On the other hand, higher temperature may decline the availability of moisture that in turn will hamper secondary infections by polycyclic pathogens. Conversely, rising temperature may provide congenial conditions for survival of higher temperature-tolerant isolates of a particular pathogen so that the latter could successfully survive, migrate, and establish at warmer geographic locations (Chakraborty, 2013). The survival of temperature tolerant pathogen isolates may also be influenced indirectly through host-plant physiology or climate change driven modifications in cropping patterns such as varying irrigations, changing sowing dates, changing tillage practices (zero tillage etc. in conservation agriculture) etc. Climate change scenarios may also control the expression of host plant resistance to pathogens through the weakening of host or pathogen that may strengthen or weaken the expression of a particular disease resistance gene (Duveiller *et al.*, 2007). This is true for situations where the expression of disease resistance genes is directly influenced by temperature, photoperiod, or precipitation (Chakraborty *et al.*, 2011; Bidzinski *et al.*, 2016).

Certain wheat pathogens, for example, *Septoria tritici*, require frequent rainfall and a consistently extended dew phase during the vegetative growth of wheat for successfully infecting the upper maximum photosynthates contributing leaves of the plant. Other wheat pathogens like *Fusarium* species require just one rainfall ranging between 2–3 mm at the time of flowering for causing severe Fusarium head blight (FHB). *P. triticina* and some other pathogens require only overnight dew to cause successful infection in wheat. Therefore, Septoria blotch could become a predominant disease in the future with warmer winter and frequent rainfall. While, in general wheat rusts and FHB would be more devastating from global warming than STB, since they are poorly dependent on occurrence of repeated and more rainfall, which is anticipated to be irregular in the future (Miedaner and Juroszek, 2021). It is speculated that the global warming would not only promote the above-ground wheat pathogens but also favor the economically significant soil-borne diseases caused by *Phoma* species, *Fusarium*, *Alternaria* etc. (Delgado-Baquerizo *et al.*, 2020).

During the last decade, a drastic change was observed in the pattern of yellow rust throughout the world including the Indian subcontinent and Europe. In India, three new *Yr9* virulent *P. striiformis tritici* pathotypes 238S119, 110S84, and 110S119 having collective virulence to wheat varieties such as Suwon 92 x Omar (*YrSU*), Strubes Dickkopf (*Yr2*, *Yr3a*, *Yr4a*) etc. were reported (Gangwar *et al.*, 2019). Likewise, Warrior and Kranich races of *P. striiformis* were detected on both triticale and wheat in many countries of Europe during 2010-11 (Hovmøller *et al.*, 2016). All these new pathotypes had additional virulence, and were more aggressive than the previous pathotypes on the then cultivated wheat varieties (Hovmøller *et al.*, 2016; Prasad *et al.*, 2020b). Subsequently, though the yellow rust epidemics somehow did not occur in India, two epidemics were reported in European countries during 2013 and 2014 and also less significant epidemics in succeeding years due to high frequency of newly evolved more aggressive and virulent pathotypes. These new pathotypes defeated yellow rust resistance in several previously resistant varieties. These findings suggest that the newly arrived isolates might have a strong propensity to cause severe yellow rust epidemics at warmer temperatures. Similar adaptations for warmer temperature are also reported for yellow rust races evolved in northern and southern France with a certain gain of the southern races in the warmer Mediterranean climate (Vallavielle-Pope *et al.*, 2018). They also observed that since 2000, *PstS1*, *PstS2* have become adapted to higher temperature and have spread worldwide. Likewise, Warrior isolates have spread to both warm and cold parts of Europe. The Warrior isolates have shown a range of infection efficiency and latent period responses to temperature and invasive *PstS2* isolates adapted to warm conditions. We have also observed similar phenomenon with *P. striiformis tritici* pathotype 78S84 which can infect and spread at higher temperature (18^{0}C) than 46S119 which thrives well at lower (15^{0}C) temperature (Bhardwaj *et al.,* 2019). Walter *et al.* (2016) also found that *PstS1* and *PstS2* were more aggressive in warmer areas. Newly emerged (after 2000) isolates of *P. striiformis tritici*, were more aggressive on all the parameters than the old ones at higher temperature. These isolates were able to cause yellow rust diseases in Western Australia and the South Eastern USA, which were otherwise supposed to be too hot for yellow rust epidemics to occur (Milus *et al.*, 2009). Likewise, leaf rust used to be the most common rust disease of wheat in Serbia until 2014; however, due to changed climate conditions, yellow rust predominated over leaf rust and reached up to 90% on the genetic collection tested in the field trials (Jevtić *et al.,* 2017).

The effect of climate change is quite evident from the fact that southern Italy in Europe faced severe stem rust epidemics during 2014-16 as several thousands of hectares area occupying durum wheat was severely infected with stem rust (Berlin, 2017). However, before that this area was thought to be stem rust-free, or if observed, it was in traces. Subsequently, stem rust outbreak occurred in central Sweden during 2017, which was assumed to be caused by a new virulent isolate originating from barberry post sexual recombination (Berlin, 2017). There are predictions that wheat stem rust is going to be a serious threat for North Western Europe (NW Europe) by the year 2050 (Davies *et al.*, 2007). These authors simulated the present-day wheat production conditions of East Africa with that of the European wheat production conditions for 2050. Based on this climate matching system the authors concluded that *P. graminis* will be a possible potential threat for wheat production in most countries of NW Europe including southern England and Ireland (Davies *et al.*, 2007).

The predicted future occurrence of a particular wheat disease for instance wheat leaf rust is not in agreement across the regions/countries (Table 1), which is understandable from the fact that the effect of the climatic conditions is not going to be parallel across different geographic locations. For example, the expected effects of climate change in Northern India might be different from those in Central India or Southern India, due to varying climatic conditions among these regions. Despite influencing the pathogen factors, climate change is also going to affect physiological growth stages in wheat, which would further influence the outcome of the effect of climate change on the wheat-pathogen system (Velásquez *et al.,* 2018). Effect of rising temperature along with changes in other abiotic factors such as, humidity, level of different gases in the atmosphere, soil factors on phenological growth stages of wheat would shift critical wheat development stages (Gouache *et al.*, 2011). For example, about 0.5-1.0^{0}C rise in temperature forced early stem elongation and flowering in wheat in Germany (Chmielewski *et al.*, 2004). Conversely, high temperature during winters could endorse and extend the growth and developmental stages in wheat, while increasing temperature and photoperiod effect on vernalization, consequently, could change the heading date (Miglietta *et al.*, 1995). Higher temperature (>34 °C) conditions augment plant senescence and thereby curtail the grain filling period in wheat (Asseng *et al.*, 2011). Despite affecting the grain filling in wheat, accelerated plant senescence also hampers the growth and pathogenesis of wheat pathogens including biotrophic fungi causing powdery mildew and rusts in particular. Though, most plant pathogens suffer under prolonged higher temperature conditions as the latter directly affect pathogen development and pathogenicity. Under such circumstances, it becomes tedious to differentiate if the activities of a particular pathogen have been directly hindered due to higher temperature or indirectly through accelerated senescence in the host plant. A similar situation arises when two or more abiotic factors like temperature, humidity, etc. have either direct or indirect effects on the outcome of a particular host-pathogen interaction. Moreover, the interaction of these factors among themselves and effects on host, pathogens and their interaction is another big challenge to address. One of the strategies to avoid the effects of climate change on the occurrence of wheat diseases is to nullify the effect of climate change in wheat by manipulating heading and flowering timing using genotypes with diverse growth and development patterns or by changing the sowing date. Such strategies would change the growth and development habits and thus, heading and flowering timings in wheat. These alterations would have direct impact on the occurrence of wheat diseases caused by fungi primarily infecting floral parts of the plant such as *Fusarium* species (West *et al.*, 2012).

2.4 Future strategies for management of wheat diseases

A shift in distribution and occurrence of wheat diseases under the influence of changing climate has emphasized the need for the development of disease prediction models which can predict the intensity and distribution of important plant diseases in real-field conditions. Moreover, improved disease management strategies including biological control and eco-friendly approaches need to be reoriented in consideration with the changing climate and implemented judiciously for sustainable crop production. Among these strategies, epidemiology-based disease forecasting, monitoring pathogen distribution and dynamics, rapid pathogen detection, and disease diagnosis could significantly contribute in effective wheat disease management (Gautam *et al.*, 2013). There is a need to develop and adopt integrated disease management tactics to minimize the dependency on hazardous chemical fungicides. Integration of plant breeding, biotechnology, chemistry, computer science, and other tools could help to counter the risk of wheat diseases in a harmonized manner. Biological control by *Trichoderma* spp., *Bacillus* spp., *Streptomyces* spp., arbuscular mycorrhizal (AM) fungi, and others could provide a sustainable and eco-friendly option of plant diseases management in changing climate scenario. Efforts have been made to manage wheat diseases by application of plant extracts and organic materials directly by their inhibitory effect on pathogens or indirectly by inducing disease resistance in plants. Biological control agents, plant extracts and many other synthetic chemicals of plant origin are reported to induce disease resistance in wheat. Cultural control methods can minimize the intensity of an epidemic or provide long-term partial management of wheat diseases. Use of healthy seeds, time of planting, frequency and amount of irrigation, balanced application of fertilizers (NPK), eradication of alternate hosts, clean cropping, crop rotation, mixed cropping, removal or avoidance of green bridges (volunteer plants, crops grown successively in one area) that may carry inoculum from one season to the other, can significantly reduce the severity and incidence of wheat diseases. All these approaches can be integrated to formulate a specific integrated disease management package for a specific wheat disease in the future under changed climate. Nevertheless, wheat breeding supported by novel molecular tools for disease resistance would remain a critical factor for developing disease-resistant and climate-resilient varieties. Increasing temperature conditions in the future may back the identification and deployment of high-temperature adult-plant (HTAP) disease resistance genes against different wheat diseases including yellow rust. The resistance conferred by HTAP resistance genes is highly durable and mostly non race specific but their expression remains moderate and varies depending upon the temperature and humidity conditions (Line and Chen, 1995). More than 80 QTLs including several yellow rust resistance genes such as *Yr18, 29, 34, 36, 39*, *48, 52*, *Yrns-B1* etc. from 33 wheat varieties have been described to possess HTAP resistance (Huerta-Espino *et al.,* 2020; Chen, 2013). There are recommendations for promoting the strategies for disease resistance breeding including screening of breeding material in a warmer climate (Bryant *et al.,* 2014; Butterworth *et al.*, 2010). Multiple disease resistance (MDR) QTLs or genes, such as *Lr67/Yr46/Sr55/Pm46*, *Lr34/Yr18/Sr57/Pm38, Lr46/Yr29/Sr58/Pm39,* and *Sr2/Yr30/Lr27*, conferring resistance to more than one disease, could be promoted to endure the threat of wheat diseases in changed climate (Silva *et al.*, 2015). Utilization of such MDR genes or QTLs could be accelerated by marker-assisted or genomic selection tools. Such an approach looks promising especially in situations where the pathogen population keeps on evolving and when there could be a shift in the occurrence of a specific disease in the future. Genomic selection (GS), a promising molecular breeding tool, is an advanced form of MAS which aims to utilize genome-wide genetic markers to envisage the effects of all QTLs and thus figure out a genomic estimated breeding value to deliver more inclusive and consistent selection for various traits including disease resistance (Miedaner *et al.*, 2019). GS for plant disease resistance is specifically encouraging since it has already been used extensively for traits like grain yield etc. Furthermore, for diseases like wheat blast, where no reliable resistance sources are available to date except some genomic regions including 2NS Translocation from *Aegilops ventricosa* that confers some resistance to wheat blast pathogen (Cruz *et al.*, 2016), the use of MAS or GS would be limited. Therefore, genome editing and other gene transfer strategies would play a significant role in developing resistant varieties for such diseases in the future (Sánchez-Martin and Keller, 2019).

3. Conclusion

Availability of current understanding about a specific host-pathosystem including the effect of other biotic and abiotic variables, without the interference of changed climate, supports effective management of wheat diseases. But with the inclusion of changing climate issues, disease management could be challenging due to the lack of thorough understanding of disease epidemiology. Addressing such challenges requires detailed information of abiotic and biotic variables, whose role is supposed to be influenced under changed climate. Such information on disease epidemiology and effects of individual climate variables could help develop disease prediction models and thus in predicting disease epidemics at a particular space and time. Despite abiotic climate variables, geographical distribution, host morphology, and physiology along with pathogens, ability to multiply, disseminate and survive will have a direct impact on the occurrence of wheat diseases and the introduction of new disease and/or pathogens. Higher UV-B radiation and elevated CO_2 levels could increase prolificacy in pathogens and thus their evolution. The existing knowledge of climate change effects on wheat diseases occurrence and management is fragmented and therefore, conclusive analysis of possible effects on changed climate on wheat diseases in the future can be based on circumstantial and limited facts. The wheat diseases like damping off, leaf rust, stem rust, Karnal bunt, Fusarium head scab, blight, and blast may increase with the rising temperature. Whereas the stripe rust incidence might decrease. However, the occurrence and prevalence of high-temperature tolerant isolates of *P. striiformis tritici* may become predominant. Considering the significant contribution of different abiotic and biotic factors in the development of plant disease epidemics, modeling tools need to be strengthened for precise and timely prediction of possible changes occurring in the agro-climate scenarios as influenced under changing climate and its effect on different host-pathosystems and impact assessment. Climate change is going to put an extra burden on organizations accountable for the prohibition and quarantine of disease-causing agents, as a plant disease management approach. In certain areas, few economically important diseases may not be favored since the climate at those locations do not let the pathogen establish and proliferate. However, there are chances that these pathogens will migrate to newer areas, establish and cause diseases that were previously absent in those areas. Therefore, exhaustive coordination is required among the researchers from different backgrounds such as plant pathologists, computer scientists, climatologists, epidemiologists, agro-meteorologists, and agronomists to further streamline the future work related to the effect of climate change on fluctuating severity, prevalence, and distribution of wheat diseases and shift in the pathogen population. Future climate change research should primarily focus on minimizing the harmful effects of both biotic and abiotic stresses on plant growth and health; and generating inclusive and pertinent prediction model (s) to predict the effect of changing climate on wheat health and productivity in the future.

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Conflict of Interest

NO

Ethical Compliance Statement

NA

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