

Review

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Review

# Addressing Wheat Yellow Rust in a Changing Climate

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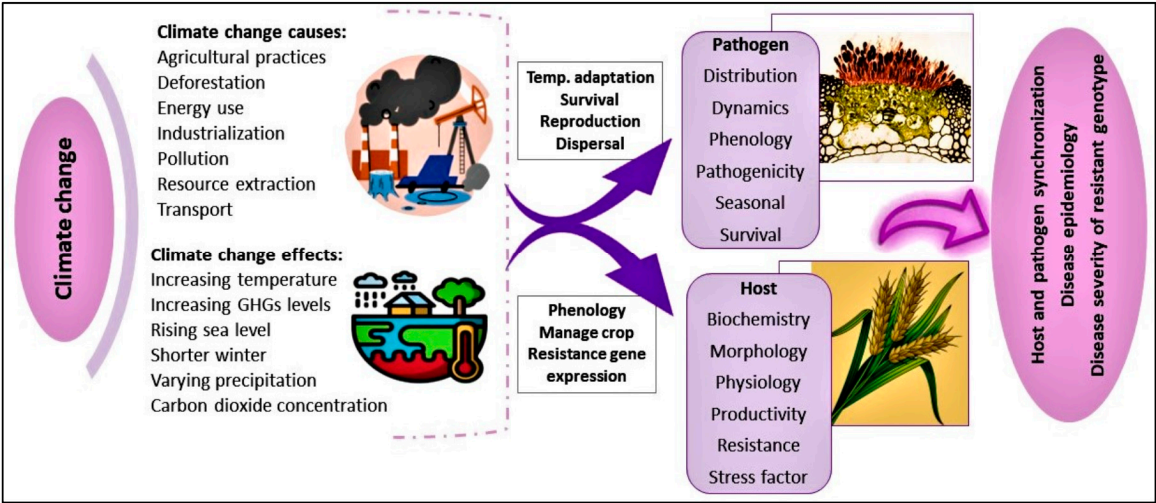
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**Abstract:** Infectious plant diseases impair ecosystems, disrupting global food production and risking human existence. *Puccinia striiformis* f. sp. *tritici* causes yellow rust disease, impacting wheat production. *Puccinia striiformis* f. sp. *tritici* (Pst)-caused yellow rust is one of the most devastating diseases of this crucial global cereal crop. Yellow rust severely impacts wheat production by tremendous yield loss threats to global food security. Yellow pustules on plant leaves evolve into big lesions that interfere with photosynthesis, resulting in stunted growth and decreased grain yield and quality. Yellow rust becomes harder to control because climate change modifies the pathogen's behavior and makes control methods previously used ineffective. Climate change conditions, such as increased temperatures and changed rainfall patterns, in addition to the escalation of extreme weather events, aid yellow rust spread and establishment, making predicting and controlling outbreaks challenging. This chapter discusses how the resistance of the host provides an effective and sustainable way of controlling wheat yellow rust under conditions of a changing climate.

**Keywords:** wheat; yellow rust; climate change; host resistance; management

## 1. Introduction

Climate change is a global challenge, with the current global temperatures being approximately 1.1°C above the pre-industrial temperature era (WMO, 2022; 2023). This thermal escalation is predominantly driven by manmade greenhouse gas releases and alterations in the land-use will persist provided the net greenhouse gas releases continue (IPCC, 2023). The impacts of climate transformation are already evident, with harmful effects to ecological systems, human populations, and structural systems. Persistent global warming is expected to intensify these dangers and associated uncertainties (IPCC, 2022). Both food supply and food security are particularly vulnerable, facing direct threats from droughts and flooding and indirect challenges from harmful insects and plant diseases (Bezner Kerr et al., 2022). Studies have indicated that climate change has negatively affected agricultural productivity around the world (Ortiz-Bobea et al., 2021). Wheat, a major food crop cultivated on 222 million hectares around the world (USDA, 2023) which is vulnerable and at risk to various diseases as a result of a changing climate. It is well-documented that climatic change patterns influence the occurrence and distribution of pathogens of economic significance (Jurossek and Tiedemann, 2013). Notably, alterations in climate profoundly impacted the epidemiology of wheat rust diseases, creating major obstacles for global wheat production (see Figure 1).



**Figure 1.** Changing climate impact on host and epidemiology of pathogens.

More frequent occurrences of extreme weather events, higher temperatures, and changing precipitation patterns are modifying the intensity, seasonality, and distribution of wheat rust epidemics (Nnadi & Carter, 2021). As much as it may extend the wheat growing season, warmer climates also promote the conditions for the propagation and spread of rust pathogens, leading to increased and intense occurrences (Miedaner & Juroszek, 2021). Moisture regimes-most notably high humidity and changing patterns of rainfall-play a decisive role in germination of spores, infection processes, and aerial dispersal; for example, high humidity enhances rust progression, and varying wind directions can disseminate spores over great distances (Sánchez et al., 2023). Further, climate-based stresses have been found to break down wheat’s natural resistance systems, making crops more susceptible to rust infections (Waheed et al., 2023). Together, these climatic changes favor the survival, growth, and transmission of pathogens, thus escalating the occurrence and severity of wheat rust diseases.

Yellow rust, caused by a fungus called *Pst*, is a big problem for wheat farmers. It usually shows up in cooler places, like northern areas or higher altitudes, especially where wheat starts to grow when it’s still a bit chilly. Table 1 shows the best conditions for this yellow rust fungus, based on past research (Roelfs et al., 1992). However, recent large-scale epidemics have emerged in warmer wheat-growing regions, driven by the evolution of high-temperature-adapted strains of *Pst* identified across different regions globally (Hovmøller et al., 2008). The capacity of wheat rusts for long-distance dispersal, rapid virulence development, and adaptation to diverse climates establishes them as a critical global threat to wheat production (Ali and Hodson, 2017).

**Table 1.** Climatic factors governing the progression of the yellow rust pathogen at various developmental stages.

Developmental Stage	Temperature (°C)			Light	Free water
	Optimum				
	Lowest		Highest		
Germination	0	9-13	23	Low	Required
Germling	-	10-15	-	Low	Required
Appressorium	-	-	(not formed)	None	Required
Penetration	2	9-13	23	Low	Required

Growth	3	12-15	20	High	Not required
Sporulation	5	12-15	20	High	Not required

Considering the global prevalence and economic significance of yellow rust, this review aims to synthesize and update the current knowledge on the disease with climate change. The primary objective is to inform the development of sustainable and effective management approaches, with a particular emphasis on utilizing host resistance to mitigate the challenges arising from climate change.

2. The Global Economic Impact of Wheat and Yellow Rust

Global wheat acreage spans approximately 222 million hectares, making it one of the most significant cereal crops worldwide in terms of both production and consumption (He et al., 2022). In the 2023-24 cropping cycle, global-scale wheat production was 784.91 million metric tons, while consumption totaled 796.44 million metric tons. The top ten wheat-producing countries include China, India, Russia, the United States, France, Canada, Germany, Pakistan, Turkey, and Ukraine. A summary of global production and consumption trends over the past seven years is presented in Table 2. Wheat is a dietary staple and the primary source of plant-derived protein for human consumption, thereby making it integral to global food security. To meet the needs of a forecasted global population size of 9.6 billion by the year 2050, wheat cultivation output must rise by 60%, despite challenges such as constrained availability of land and water and the effects of a changing climate (Savadi, 2018). Under these changing climatic conditions, wheat production is increasingly threatened by a range of biotic and abiotic factors, with the yellow rust pathogen among the most severe biotic challenges.

Table 2. Global wheat production and consumption during 2017-18 to 2023-24.

Years	Production (Million metric tons)	Consumption (Million metric tons)
2017-18	761.54	742.37
2018-19	730.92	735.31
2019-20	759.39	745.71
2020-21	773.09	786.57
2021-22	780.05	791.16
2022-23	789.17	790.93
2023-24	784.91	796.44

Source: (Production of wheat worldwide 2023/24 | Statista; Total wheat consumption worldwide 2023/24 | Statista).

Yellow rust, also referred to as “Stripe rust” due to the yellow-to-orange coloration of the uredinia which forms characteristic “yellow stripes” on infected leaves (Figure 2), spores freed from the uredinia are capable of reinfecting the same plant, and other surrounding plants within that field, or spreading to host plants situated hundreds of kilometers from the source. Yellow rust has been documented in more than sixty countries on all continents except Antarctica (Chen, 2005). An international survey conducted between 2000 and 2009 on the severity and frequency of yellow rust outbreaks included data from more than 60 countries (Wellings, 2011; Boshoff et al., 2019).





**Figure 2.** source Wiik, L. (2009). *Control of fungal diseases in winter wheat* (Vol. 2009, No. 2009: 97).

The survey revealed that large-scale yellow rust outbreaks are common two to three times every five years across many wheat-growing regions worldwide, and the disease can cause crop losses of 5% to 10%. About 88% of wheat produced worldwide has been estimated to be threatened by rust diseases, which cause a yearly economic loss of about \$1 billion (Wellings, 2011; Beddow, 2015; Schwessinger, 2017). Further, a recent world survey of pathogens and pests causing damage to prominent food crops indicated yellow rust among the major pathogens, responsible for yield losses above 1% globally (Savary et al., 2019).

Major epidemics of yellow rust have occurred during the last twenty years in major wheat-growing areas of the world. Prominent outbreaks have been reported in China (Li & Zeng, 2002), South Asia (Hussain et al., 2004; Duveiller et al., 2007; Aggarwal et al., 2018; Tariq-Khan et al., 2020), the Middle East and Central Asia (Solh et al., 2012), Central and West Asia (Chen & Kang, 2017), Europe (Solh et al., 2012), Africa (Pretorius, 2004; ICARDA, 2011; Solh et al., 2012), Australasia (Murray & Brennan, 2009; Solh et al., 2012), South America (Ochoa et al., 2007; Wellings, 2011), and North America (Line, 2002; Chen, 2005, 2007; Chen & Kang, 2017; Brar et al., 2019).

### 3. Climate Change and Wheat Yellow Rust

#### 3.1. Emergence of High-Temperature-Adapted Pst Strains and Rust Expansion

Historically, Pst is viewed as a kind of pathogen that can amoeba in mild to cooler climates and thereby restrict its proliferation by increased temperatures (Dennis, 1987). So, its adaptability to warmer conditions increases the chances of its spread into new places considerably (Vidal et al., 2022). Culminating that, the spreading of a single strain of Pst, PstS1, in North America in 2000 and in Australia in 2002, as well as the following spread by a genetically near identical strain PstS2 into Europe and Asia, is said to be one of the fastest and largest dispersals of a crop pathogen in history (Hovmøller et al., 2023). They both have adapted to the causes of increased temperatures and have been mainstream in the southern central region of U. S States since 2000, a period that did not flag the disease as a significant concern (Milus et al., 2009; Chen, 2005). Research, both experimental and field studies, thus, has evidenced that infectious plant diseases may be very responsive to temperature fluctuations (Chaloner et al., 2020), and much evidence exists on their predicted range

extension under future climate change scenarios (Lafferty, 2009; Sturrock et al., 2011; Ghelardini et al., 2016; Wyka et al., 2017; Pathak, 2018;).

Traditionally, before 2000, yellow rust was mainly confined in the U.S. to the Pacific Northwest and California. However, after 2000, the disease gradually spread into southern-central states and across the central Great Plains (Chen, 2005). First, this debate must assume that *Pst* is an important pathogen of cereal crops in the temperate regions, where it was considered to be cool-weather-loving, but with recent initiatives, *Pst* may have been adapted to heating climates (Milus et al., 2006). The comparison between 1970s isolates and 2003 isolates showed that post-2000 isolates were found to germinate significantly faster and had shorter latent periods at 18 degrees Celsius, while not much difference was seen at 12 degrees Celsius. A recent study has also shown that *Pst* recovers from heat stress more rapidly than previously thought (Gardner et al., 2023).

Yellow rust has been the dominant wheat disease in Serbia since 2014, a trend linked to increasing winter temperatures—namely, increases to 4.2°C in January and 6.1°C in February compared to the long-term averages of -0.1°C and 1.8°C, respectively, since 1964 (Jevtić et al., 2017). The disease has also been more commonly reported in Northwestern Russia (Gulyaeva et al., 2021), West Siberia (Ivanova et al., 2021), the Volga area, and the Central Chernozem region (Druzhin, 2010; Zeleneva et al., 2022), spreading beyond its previously predominant status in the North Caucasus. These transformations have most probably been brought on by global climate change and its effects on the distribution of the disease. Warrior race wheat yellow rust, which is the most dominant strain in Serbia, is shown to have profuse adaptability across ambient temperatures, thriving in both warmth, such as in Spain, and coolness like Sweden (Jevtić et al., 2017; Hovmøller et al., 2016). These are said to be categorized under the thermal generalists, showing a peak in infection efficiency at 10°C and 15°C (de Vallaville-Pope et al., 2018). Before 2004 in France, the *Pst* population adapted to local temperature variations, resulting in notable spatial differences in the interactions between pathotype and temperature that influenced urediniospore germination and infection efficiency, especially between the southern and northern regions of France (Mboup et al., 2012). Similar adaptations to temperature ranges have been observed in *Pst* isolates from the US and Australia (Loladze et al., 2014; Sharma-Poudyal et al., 2014). Recently, *Pst* has demonstrated diminished importance in the wheat growing seasons throughout the Nordic and Baltic areas (Strandberg et al., 2024).

Historically, wheat yellow rust was regarded as a minor concern along the eastern shores of Zhejiang and Jiangsu Provinces in China, with its progression being slow and often interrupted by early April. However, by early May in 2019, the severity of the disease had not increased, probably due to the warmer climatic conditions favoring the high-temperature-adapted isolates (Ju et al., 2022; Zhao & Kang, 2023). Since 2012, there have been some scattered incidences of different *Pst* pathotypes in China, where 126 *Pst* isolates from 12 provinces have exhibited high-temperature tolerance. This pathogen population has shown significant adaptation to high temperature levels, thriving well at temperatures above the critical 23°C threshold (Zhang et al., 2013).

The dissemination of rust pathogens has grown more alarming, with reports indicating that *Pst* has extended to South Africa, a phenomenon most likely associated with changes in rainfall patterns (Boshoff et al., 2002). To this, both stem rust and yellow rust are now threatening to set up homes in previously uninfected regions as milder winters enable these pathogens to make it through the harsher periods (Ma et al., 2015; Novotná et al., 2017; Prank et al., 2019). This indicates an increasing susceptibility of wheat crops while climate conditions keep evolving (Juroszek et al., 2020). Predictions for 2050 suggest that climate change may significantly redefine major wheat-producing areas, allowing rust fungi to grow and expand into new regions (Ortiz et al., 2008).

In north of India, the current epidemic of yellow rust in Punjab has been associated with the break of the new pathotype (78S84), which can infect wheat at elevated temperatures. The disease initially appeared during late December, as a result of favorable climatic conditions and rising temperatures (Prashar et al., 2007; Jindal et al., 2012). Severe weather occurrences, including

heatwaves, have also been speculated to prefer particular Pst lineages, making pathogen populations change temperature optima (Strandberg et al., 2024).

### 3.2. Pathogen Survival, Reproduction, and Increased Aggressiveness

Rain and temperature are critical environmental elements that impact Pst germination, infection, and survival (Lyon & Broders, 2017). Increased winter temperature is known to support overwinter survival of pathogens in the growing season (Gladders et al., 2007). In Canada, rust pathogens do not generally survive the winter; however, moderate winters will allow for winter survival and/or the advanced initiation of rust and perhaps enhanced severity of disease (Boland et al., 2004). In a similar vein, enhanced off-season rainfall can contribute to more suitable conditions for the persistence of pathogens during summer in some parts of Australia. Temperature's effect on Pst's reproductive cycle is well established, with both sexual and asexual phases being sensitive to temperature. Research has established that telia and teliospore production is enhanced under high-temperature conditions (McDonald & Linde, 2002; Chen et al., 2021).

Aggressiveness, one of the measurable elements of pathogenicity, is the level of injury caused to host plants (Andrion et al., 2007; Pariaud et al., 2009). It is an important biological characteristic that indicates the degree to which a pathogen can develop, become established, and reproduce in a host plant. It covers several infection-related traits associated with the fitness of the pathogen as a whole, such as how well it infects, when it will produce symptoms (latency period), how quickly it produces spores, how long it can continue to infect, and the lesion size it produces (Pariaud et al., 2009). Due to this, aggressiveness is central in the constant evolutionary struggle between hosts and pathogens. Scientists can measure this characteristic at different developmental stages of the plant, both during seedling development (Milus et al., 2006; de Vallavieille-Pope et al., 2018) and in adult plants (Pariaud et al., 2009b; Azzimonti et al., 2013).

Temperature is crucial in the way pathogen evolution occurs, especially in determining their capacity to adapt to different temperature environments (Zhan & McDonald, 2011; Yang et al., 2016). It also determines how virulent these pathogens can be (Schade et al., 2014). The relationship between temperature and virulence is well established, particularly with wheat yellow rust. Warmer temperatures have been found to enhance the virulence of Pst, highlighting the fungus's ability to adapt to increasing temperatures (Mboup et al., 2012). New and highly virulent Pst pathotypes, with wider virulence and greater adaptation to higher temperatures, have appeared in recent years (Milus et al., 2009; Walter et al., 2016). For example, in the eastern United States, Pst populations are still adapting under conditions of warming, demonstrating enhanced fitness and virulence, even when certain resistance genes are present (Lyon & Broders, 2017). Likewise, Latvia has indicated the appearance of more virulent Pst races like 'Warrior,' 'Kranich,' and 'Triticale' (Feodorova Fedotova & Bankina, 2018).

Some Pst strains, especially those in the PstS7 lineage, are considered thermal generalists with high performance at a wide temperature regimen-instead of being thermal specialists like older isolates (de Vallavieille-Pope et al., 2018). In Serbia, there was a remarkable rise in the incidence of highly pathogenic Pst races in 2023 (Župunski et al., 2024).

In China, the dissemination of G22-virulent pathotypes has proceeded rapidly, their spread to new areas being due to boosted infectivity and enhanced virulence (Liu et al., 2012; Li et al., 2016; Wang et al., 2017). Among the most prevalent and virulent races detected in major wheat-producing regions are G22-9 (also referred to as CYR34), CYR32, and CYR33, whose occurrence has been reported several times in major regions (Liu et al., 2017; Bai et al., 2018; Huang et al., 2020). Moreover, the Su11 race group remains dominant in Xinjiang, showing excellent fitness and good adaptability in a wide range of wheat cultivars and environments (Ma et al., 2023).

New five Pst races have been identified by recent reports from India, including 46S117, 110S119, 238S119, 110S247, and 110S84, of which the most widespread and virulent is race 110S119, characterized by its high rate of growth (Gangwar et al., 2016). Research conducted to analyze spore germination at different temperatures, 5°C, 10°C, 15°C, and 20°C, has found that the germination



reached a peak at 15°C, while at other temperature levels, germination sharply decreased (Anand et al., 2023).

It was recently discovered that *Pst* aggressiveness in the Middle East and Mediterranean is temperature-dependent, with no variation between isolates from low- and high-altitude origins (El Amil et al., 2022). Isolates LB6 from Lebanon, TK3 from Turkey, and SY2 from Syria showed high aggressiveness at high temperatures regardless of their native altitudinal origins (El Amil et al., 2022).

There has been a sharp rise in aggressiveness of yellow rust in Egypt in recent times, with the disease spreading to all parts of the country, including areas of hotter and drier climates like Upper Egypt (Esmail et al., 2023). Between 2018 and 2020, 42 *Pst* races were reported, with six novel aggressive strains (72E8, 135E16, 151E80, 160E173, 224E191 and 238E143) emerging for the first time (Esmail et al., 2021).

### 3.3. New Strains and Pathotypes

Rising temperatures have facilitated the development of more virulent *Pst* races globally, significantly affecting wheat crop productivity (Milus et al., 2009). Earlier to 2000, virulence and molecular investigations regarding isolates from major wheat growing regions of Europe, Australia, and North America consistently documented clonal *Pst* populations, characterized by closely related pathotypes and low genetic diversity, primarily driven through single-step mutations (Steele et al., 2001; Hovmöller et al., 2002; Chen, 2005; Enjalbert et al., 2005; Chen et al., 2010; Ali et al., 2014a; Hubbard et al., 2015; Hovmöller et al., 2016). However, in the past two decades, novel virulence profiles have notably emerged, and more aggressive strains have emerged worldwide. Notably, the PstS1 and PstS2 strains emerged rapidly throughout the U.S. (Chen et al., 2002; Markell and Milus, 2008), Australia (Wellings, 2007), and Europe (Hovmöller and Justesen, 2007) within a short timeframe of three years at the beginning of the 2000s. These strains are distinguished by their adaptation to high temperatures, which is atypical for this pathogen (Markell and Milus, 2008; Milus et al., 2006, 2009).

The appearance of *Pst* pathotypes PstS1 and PstS2 has allowed the yellow rust pathogen to become established in areas previously deemed unsuitable for its growth (Milus et al., 2006). These pathotypes have also greatly widened their host range and geographic limits, now being a serious threat to wheat cultivation across the US and regions in the African and Australian continents (Bahri et al., 2009; Wellings, 2011; Chen et al., 2014; Walter et al., 2016). Another analysis (Yahyaoui et al., 2002), considering *Pst* populations in Syria and Lebanon between the years 1994 and 1999, showed an abundant pathotypic diversity, where 25 pathotypes were found to exist in Syria and 11 in Lebanon. Various new versions also appeared throughout this time with virulence attributes like v2, v6, v7, v8, and v9-signifiers later ascribed to the PstS2 pathotype (Hovmöller et al., 2011). PstS2 first emerged in the East African region during the early 1980s and is now among the most global and long-standing yellow rust pathotypes (Ali et al., 2014a; Walter et al., 2016).

During the period 2005-2006, 268 *Pst* isolates from 12 countries located in the western and eastern Mediterranean regions were studied. This analysis resulted in the characterization of twelve pathotypes, with the interesting “PstS2-v27” among them (Bahri et al., 2009). A point of note was that eight pathotypes occurred solely in the eastern Mediterranean, emphasizing the rich genetic diversity of the region and its status as a hotspot for new *Pst* pathotypes to emerge.

A set of 268 *Pst* isolates gathered from 12 nations in the western and eastern Mediterranean were tested between 2005 and 2006, leading to the detection of twelve different pathotypes, such as the significant “PstS2-v27” (Bahri et al., 2009). Eight of these 12 pathotypes were confined to the eastern Mediterranean region, highlighting high *Pst* diversity of the region and its role as a key region for the origin of novel strains. One Israeli sample contained virulence genes (i.e. v2, v6, v7, v8, v9, v25, and v27), corresponding to the PstS2-v27 pathotype.

New variants and pathotypes of PstS1/PstS2 have been established in North African and West Asian regions, acquiring additional virulence to *Yr* resistance genes, including *Yr1*, *Yr3*, *Yr10*, and *Yr27*, few of these are extensively used in wheat breeding programs (Singh et al., 2004; El Amil, 2015).



Current variants of PstS1/PstS2 include strains such as PstS1/2b (North America, Australia), PstS1/2-*v1* (East Africa), PstS1/2-*v3* (East Africa), PstS1/2-*v27* (East Africa, West Asia, North Africa), along with several other combinations involving *v1*, *v3*, *v10*, and *v27* across various regions (GRRC, 2022). These emerging pathotypes highlight the importance of the ongoing adaptation of *Pst* to changing environmental conditions and its increasing influence on wheat production around the world.

### 3.4. Regional Impact of Yellow Rust

Reports indicate that yellow rust epidemics have originated in distant areas, appearing either in regions where they were previously absent or reappearing in more virulent forms. (Bahri et al. 2009; Hovmøller et al. 2023b). The emergence of new strains such as PstS1 and PstS2 has enabled *Pst* to spread into warmer regions previously considered unsuitable for the progression of the disease (Milus et al., 2006). In recent decades, numerous yellow rust epidemics have occurred globally, with significant impacts on wheat production. In North America, yellow rust has increasingly become a significant issue in wheat production (Chen and Kang 2017). From 2000 to 2007, yellow rust was reported annually in at least 15 U.S. states, resulting in estimated yield losses surpassing 6.5 million tonnes (Chen et al., 2010). In the 2010 epidemic, however, yield losses were estimated at 2.2 million tonnes, with additional fungicide costs totaling around \$30 million solely in Washington State (X.M. Chen, pers. comm.). Although yellow rust posed a lesser threat in the Great Plains in 2011, largely due to extensive drought conditions, the Pacific Northwest had a severe impact than in 2010. Yield losses in susceptible varieties were projected to surpass 70%, according to data from experimental plots and growth stage assessments. In the 2012 growing season, yield reductions in highly susceptible wheat varieties were forecasted to reach 50%. In Canada, the most widespread and severe outbreaks were reported in western Canada during 2010 and 2011 (Brar et al. 2019). In South America, Yellow rust has posed a substantial challenge in several countries (Wellings 2011). While *Pst* occurred sporadically in Uruguay from its initial detection in 1929 until 2016, it has since caused widespread epidemics in Uruguay and Argentina starting in 2017 (Carmona and Sautua 2018; German et al. 2018, 2021).

Europe is well-known for its extensive research on yellow rust and its recurring epidemics, particularly in the northwestern region. The Warrior/Ambition race was first identified during the 2009/2010 season in the UK, Germany, Denmark, France, and Scandinavia, and into Spain, leading to widespread epidemics and severe crop damage (Vergara-Diaz et al., 2015; Hovmøller et al., 2016). The Kranish race, identified in 2011, contributed to disease outbreaks across many European countries (Solh et al. 2012; Gomes et al., 2018). In Portugal, *Pst* had been absent for two decades but has since become a major threat to wheat and triticale production beginning in 2013 (Gomes et al., 2018). Italy has experienced at least three significant outbreaks of yellow rust over the past decade (M. Maccaferri, personal communication). In 2019, severe yellow rust epidemics were reported across several European regions (Anonymous 2019). Although less frequent in Eastern Europe, yellow rust has caused notable damage in countries. In Serbia, yellow rust predominated over leaf rust following a shift in climate conditions in 2014, with disease severity reaching up to 90% in field trials (Jevtić et al., 2017; Župunski et al., 2016).

Australian farmers spent an estimated \$40-90 million annually between 2003 and 2006 on fungicides (Wellings 2007) to manage yellow rust. Pathotypes carrying virulences *v17* and *v27* were identified as serious threats to wheat-producing regions in Australia. Despite recurring outbreaks and occasional appearance of nonnative pathotypes, Australia's countrywide breeding program focused on rust resistance has been largely effective in mitigating the most severe effects of yellow rust epidemics.

In Africa, yellow rust remains a significant problem in many countries located in the northeast, northwest, and South Africa, and in the south. A major outbreak occurred in Morocco in 2009, and since 2010, the disease has spread widely throughout the East African region, causing considerable financial losses, particularly in low-input subsistence farming systems (Singh et al., 2016). The 2010

outbreak in Ethiopia caused production losses ranging from 67-100% on commercial wheat varieties, costing over \$3.2 million on fungicide treatments (ICARDA 2011; Solh et al. 2012).

Facultative winter wheat in the CWANA (Central and West Asia and North Africa) region of southern Kazakhstan and Uzbekistan has regularly experienced yellow rust outbreaks, with particularly intense outbreaks during 2009 and 2010. The loss of resistance to *Yr27* in wheat cultivars such as PBW343(India), Inquilab 91(Pakistan), and Chamran (Iran) was documented from 2002 and 2004. While yellow rust epidemics were sporadic in certain zones, adverse climatic conditions likely limited the speedy increase of pathotypes carrying *v27* virulence until 2009, when favorable climate led to widespread outbreaks in at least 11 countries in the CWANA region. These favorable conditions persisted into 2010, characterized by less severe winters and sufficient rainfall across CWANA countries, leading to early yellow rust outbreaks. The 2010 yellow rust pandemic led to significant yield losses throughout key wheat-producing regions in CWANA and the Caucasus, with Syria experiencing particularly severe losses due to the widespread cultivation of Cham 8 (carrying *Yr27*), which covered more than 70% of the wheat acreage. Even with conducive conditions in 2011 and 2012, significant yellow rust outbreaks did not materialize, highlighting the interannual variation of crop diseases and their effects. Key varieties were susceptible in the major wheat-producing countries of the Central Asian and Middle Eastern region. A catastrophic epidemic broke out in Turkey's Central Plateau, where Gerek 79, a susceptible cultivar, was the most common. Identified in East Africa as early as the 1980s (Walter et al., 2016), the closely related clonal lineages PstS1 and PstS2 have driven significant epidemics around the world from the year 2000 onward (Hovmöller et al., 2011).

In China, multiple large-scale yellow rust outbreaks have been documented (Li and Zeng 2002), including a severe outbreak in 2002 that affected 6.6 million hectares across 11 provinces (Chen 2020). In South Asia, yellow rust is a significant challenge to wheat farming in India, Pakistan, Nepal, and southeastern Afghanistan.

Yellow rust has grown to become more widespread in the cooler northern parts of India, infesting around 10 million hectares of wheat (Bhardwaj et al., 2019). Punjab suffered from a major yellow rust epidemic in 2008, and the disease persisted to spread over different regions of the country throughout the 2010–2011 wheat growing seasons (Aggarwal et al., 2018). A similar epidemic had already been seen in Pakistan in 2005. Yellow rust epidemics of different magnitudes were also noted in several countries in Central and West Asia in 2010 (Rahmatov et al., 2012; Chen & Kang, 2017), with especially severe instances in Syria and Lebanon (El Amil, 2015). Turkey was also severely affected, with substantial epidemics in 2007, 2009, and 2010 that resulted in huge wheat yield losses (Solh et al., 2012).

### 3.5. Effects of Elevated GHGs and Abiotic Factors on Host-Pathogen Dynamics

Increased global temperatures, elevated levels of atmospheric carbon dioxide, and the occurrence of more intense and frequent weather events such as droughts and floods have the potential to greatly affect how plants defend against disease caused by pathogens (Dossa et al., 2015). These climatic changes can also have the potential to change the dynamics of plants and pathogens, how and where disease occurs, and how disease range increases (Chakraborty, 2005; Burdon et al., 2006; Garrett et al., 2006; Cowl et al., 2008; Eastburn et al., 2011).

Between 2016 and 2019, conditions of severe winter temperatures exposed discernible variation in the susceptibility of wheat genotypes to obligate pathogens, with implications for the disease-susceptible role of climate (Jevtić et al., 2020). More extensive climate change patterns, including increased temperatures, elevated atmospheric CO<sub>2</sub> concentrations, and enhanced frequency of extreme weather events such as flooding and drought, also have the potential to impact the ability of plants to resist pathogens (Dossa et al., 2015). These climatic shifts are expected to alter host-pathogen interactions and shape the temporal and spatial dynamics of disease outbreaks (Chakraborty, 2005; Burdon et al., 2006; Garrett et al., 2006; Cowl et al., 2008; Eastburn et al., 2011). Worldwide epidemic spreads of rust diseases under regions having elevated levels of ambient ozone (O<sub>3</sub>) levels confirm

prospective interactions of the mentioned factors and justify parallel breeding efforts focusing on increasing resistance against rusts, as well as tolerance towards ozone, in wheat (Mashaheet et al., 2020). Ethiopian studies proved that wheat lines showing yellow rust resistance had a greater production under conditions of drought than vulnerable varieties (Abro et al., 2017). Moreover, differences in bread wheat response to heat stress and susceptibility to yellow rust have been noted in Egypt, which means that it is feasible to breed for heat stress tolerance in combination with rust resistance without negatively impacting yield (Megahed et al., 2022).

#### 4. Host Resistance as a Primary Control Strategy

The warming global climate has created conditions increasingly conducive to the establishment and spread of the wheat yellow rust pathogen (Chakraborty et al., 2010). While various control strategies exist, among these, developing and promoting resistant wheat varieties remains the most efficient and sustainable method from both a cost and environmental perspective (Chen, 2013). Wheat resistance to yellow rust is of two categories: All-Stage Resistance (ASR) and Adult-Plant Resistance (APR). To date, over 300 resistance-associated specific genes or associated trait loci (QTL) have been identified, with 86 genes (*Yr1–Yr86*) officially named (Zhu et al., 2023).

ASR genes, including *Yr1*, *Yr2*, *Yr3a/b/c*, *Yr4a/b*, *Yr6*, *Yr7*, *Yr9*, *Yr10*, *Yr17*, *Yr24/Yr26*, and *Yr27*, were extensively utilized in breeding programs worldwide. However, ASR genes are highly vulnerable to becoming compromised by the rapid adoption of *Pst* populations (Hulbert and Pumphrey, 2014). In many regions, the development of virulent *Pst* pathotypes has rendered most ASR genes ineffective (Wang and Chen, 2017; Chen, 2020). Conversely, APR genes, which generally confer partial resistance, have demonstrated greater durability compared to ASR genes. A potential solution to counteract the loss of rust resistance is the deployment of APR genes, active at the later growth stages and providing broader, more durable resistance (Brown, 2015; Niks et al., 2015). Among APR types, high-temperature-triggered resistance in mature plants (HTAP) is particularly significant. HTAP resistance is durable with non-race-specificity, and the resistance levels increase as plants mature and environmental temperatures rise (Chen, 2005, 2013). Wheat varieties carrying HTAP resistance display susceptibility to *Pst* at the juvenile plant stage at low temperatures during the adult-plant stage. However, they exhibit strong resistance at higher temperatures during the post-seeding adult stage (Chen, 2007, 2013).

Currently, twenty-five *Yr* resistance genes along with multiple QTLs have been identified as associated with APR. Among these genes, *Yr18*, *Yr36*, *Yr52*, *Yr59*, *Yr62*, *Yr78*, and *Yr79* are reported to be effective in conferring HTAP resistance (Santra et al., 2008; Fu et al., 2009; Krattinger et al., 2009; Ren et al., 2012; Lu et al., 2014; Zhou et al., 2014; Dong et al., 2017; Wang and Chen, 2017; Feng et al., 2018; Liu et al., 2018, 2019, 2020; Mu et al., 2020). Rising global temperatures are expected to impact wheat growth stages, accelerate leaf senescence, and potentially disrupt yellow rust development. However, the pathogen itself has demonstrated an ability to adapt to higher temperatures, emphasizing the importance of incorporating HTAP resistance genes into wheat breeding programs to enhance resilience (Chakraborty and Newton, 2011; Asseng et al., 2011; Juroszek and von Tiedemann, 2013; Khanfri et al., 2018). The combination of all-stage resistance (ASR) and high-temperature adult-plant (HTAP) resistance presents a compelling method of acquiring durable, long-term protection against yellow rust in wheat, a more critical objective as climate change continues to compromise crop defense mechanisms (Bariana et al., 2022).

#### 5. Conclusion and Way Forward

The increasing number of yellow rust epidemics, induced by an airborne fungal pathogen, emphasizes the imperative for new and sustainable control measures to safeguard world wheat production and global food security. This yield-limiting disease causes serious damage and is becoming increasingly difficult to control as climate change modifies pathogen behavior and diminishes the effectiveness of conventional control measures. A holistic solution is needed to solve

this multifaceted problem. One of the most powerful and enduring solutions is to build host resistance by developing rust-resistant wheat varieties with a diverse array of resistance genes. Moreover, incorporating climate-adaptive disease management practices, such as enhancing forecasting systems and synchronizing breeding programs with climate forecasts, will be critical to keeping up with the changing patterns of disease caused by global warming.

Developing robust disease surveillance systems and employing sophisticated diagnostic technologies are key to detecting outbreaks early and acting swiftly to new threats. Adopting sustainable agricultural practices, such as crop rotation and effective irrigation, can also serve to contain the spread of pathogens while enhancing the resilience of agricultural systems. Encouraging collaboration between disciplines and establishing healthy policy frameworks are as critical as bridging knowledge gaps, boosting innovation, and implementing control approaches efficiently. Putting these efforts as priorities will help stakeholders make their wheat production systems more resilient, as well as play a significant role in global food security.

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