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Population composition and virulence of *Puccinia striiformis* f. sp. *tritici* in Kazakhstan

Shynbolat Rsaliyev[1]*, *Aralbek Rsaliyev*[2], *Rakhim Urazaliev*[1],
Saltanat Dubekova[1,3], *Akerke Serikbaykyzy*[3]

[1]*Kazakh Research Institute of Agriculture and Plant Growing, Almalybak, Almaty region, Kazakhstan*
[2]*Research Institute of Biological Safety Problems, Gvardeisky, Zhambyl region, Kazakhstan*
[3]*Kazakh National Agrarian Research University, Almaty, Kazakhstan*

**Corresponding author: shynbolat63@mail.ru*

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Abstract: In recent years, epidemics of wheat yellow rust caused by *Puccinia striiformis* f. sp. *tritici* (*Pst*) have been observed in major winter wheat-producing regions in Kazakhstan. However, there is currently very little information about the racial composition and virulence of *Pst*. The global emergence of aggressive and genetically diverse *Pst* races leads to different seasonal and geographic patterns of the pathogen, making cultivated wheat varieties vulnerable to the pathogen and potentially causing yellow rust epidemics. Three periods with different characteristic dominant *Pst* races were distinguished in Kazakhstan during 1985–2022. The first period covers 1985–2000, when in the southeast of the country, the main *Pst* races were 7E156 (31/1.5), 7E158 (A-8/5), 39E158 (X/1.5) and 86E16. In the second period (2001–2010), the crops were dominated by races 7E159, 31E159 and 47E224, which showed virulence to varieties with resistance genes Yr9 and Yr18. In the third period (2018–2022), the most dominant races in the fungal population were 7E159, 39E158, 79E73, 79E179, and 111E158, exhibiting virulence to varieties with the Yr26 and Yr27 genes. In the background of field infection, the resistance genes Yr5, Yr10, and Yr15 remain reliable in ensuring resistance; the Yr4, YrSp, and YrND sources are also highly effective against the *Pst* population.

Keywords: winter wheat; yellow rust; population; *Pst* race; Yr gene

One of the most dangerous diseases of wheat is yellow rust; the causal agent is the fungus *Puccinia striiformis* f. sp. *tritici* (*Pst*) (Roelfs et al. 1992; Wellings 2011). New races of this disease are rapidly spreading across continents, causing serious epidemics of the disease in many countries (Hovmøller et al. 2016; Volkova et al. 2020; Zhang et al. 2020; Cat et al. 2021; Sufyan et al. 2021). In Kazakhstan and other Central Asian countries, the pathogen occurs almost every year, excluding extremely dry years. In favourable years, massive development of yellow rust often occurs in the southern and southeastern regions of Kazakhstan and Uzbekistan (Ziyaev et al. 2011; Sharma et al. 2013; Kokhmetova et al. 2018). In addition, many winter wheat varieties approved for use in Kazakhstan are susceptible to the pathogen *Pst* (Koyshybaev 2018).

In Kazakhstan, yellow rust is usually found in the southern and southeastern regions, where winter wheat is mainly grown. In this region, intensive spread of the pathogen was recorded on irrigated crops in 2000 and 2002 (Koyshybaev 2018). Both

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global climate change and other evolutionary factors facilitate the massive spread of rust worldwide. The main factor causing rust epidemics is the emergence of new virulent races (pathotypes) (Hovmøller et al. 2016; Liu et al. 2017; Omrani et al. 2018; Cat et al. 2023), leading to the loss of resistance of commercial wheat varieties: Bogarnaya 56, Almaly, Zhetysu, Naz, Steklovidnaya 24 (Dubekova et al. 2021).

Spores of rust fungi can be transported over long distances, sometimes across oceans (Wellings 2007). The spread of yellow rust in Kazakhstan is associated with the development this disease in Central Asia. Thus, in favourable years in the second and third decades of April, this disease appears in Uzbekistan, then spreads with air currents to the Turkestan and Zhambyl regions and, after 20–30 days – to the foothill zone of the Almaty region. For zoning the territory of the republic according to the threat and frequency of disease epidemics, it is important to analyze their long-term dynamics by region (Koyshybaev 2018). In recent years (2020–2023), due to dry weather conditions, yellow rust on winter wheat has not developed to epidemic levels in the south and southeast of Kazakhstan. However, the massive development of this disease in neighbouring countries creates suitable conditions for the penetration of fungal spores into the territory of Kazakhstan. In addition, winter wheat varieties cultivated in Kazakhstan (Almaly, Bogarnaya 56, Krasnovodopadskaya 90, Sapaly, Steklovidnaya 24, Zhetysu) are strongly affected by virulent *Pst* races against an infectious background.

New *Pst* races threaten wheat production because they have adapted to higher temperatures and are not, as before, limited to cool climates. A feature of new *Pst* races in recent years is their virulence to wheat varieties with the Yr27 gene (Wan et al. 2007; Ziyaev et al. 2011). Therefore, it was necessary to study the natural population of *Pst* by identifying the fungus's most dominant and virulent races and determining the effectiveness of resistance genes using phytopathological methods. Our research aims to compare old collectable wheat *Pst* races for 1985–2000 and new races for 2001–2010 and 2018–2022, as well as determine the effectiveness of yellow rust resistance genes in Kazakhstan using isogenic Yr lines.

MATERIAL AND METHODS

Collection of yellow rust samples. Surveys of winter wheat crops to monitor yellow rust were carried out in 2018, 2019 and 2022 in a total of 6 areas of two regions of the Republic of Kazakhstan, namely Almaty and Zhambyl regions, where yellow rust usually spreads. Monitoring was carried out on commercial winter wheat varieties crops during disease development in May and June. At each point, about five to six pieces of a leaf blade about 8–10 cm long were collected, having pustules with an obvious manifestation of the disease. Samples were air-dried at room temperature for at least 24 h and then stored in paper bags. The dried samples were delivered to the Research Institute for Biological Safety Problems and stored in a refrigerator at 4 °C until further use in the isolation process. For the study, 123 viable single-pustule *Pst* isolates were used, which were collected in 2018–2022 in the areas of Almalybak – N43°13'09" E76°41'17" (48 isolates), Betkaynar – N43°12'29" E74°27'55" (15 isolates), Rgaity – N45°41'05" E81°51'33" (15 isolates), Kainar – N42°57'05" E73°14'20" (7 isolates), Talapty – N42°35'28" E70°51'27" (14 isolates), Aspara – N43°02'42" E73°33'35" (24 isolates). In addition, collection races of the *Pst* pathogen were used for experiments, in the amount of 46 races, collected and differentiated in 1985–2010 in southeast Kazakhstan.

Differentiation of *Pst* races. Determination of *Pst* races was carried out according to the standard method (Johnson et al. 1972) using two sets of differentiator varieties: International (Chinese 166, Lee, Heines Kolben, Vilmorin 23, Moro, Strubes Dickkopf, Suwon 92/Omar) and European (Hybrid 46, Reicherberg 42, Heines Peko, Nord Desprez, Compair, Carstens V, Spaldings Prolific, Heines VII). After the occurrence of symptoms of the disease in a susceptible control variety of Morocco, the resistance of plants to yellow rust was evaluated using established scales. In laboratory conditions, the infection type (IT) in wheat seedlings with yellow rust was determined on the Gassner and Straib scale (1929).

The IT data of seedling reactions were analyzed using the Differentiation method of *Pst* races (Johnson et al. 1972). The decimal system of numbering was used for the designation of races. The base of this system is two types of signs: Avirulent type (A) signed as "0" and Virulent (V) as "1". When marking races, it is recommended to first write the number in the decimal system according to the International set, then the number according to the European set with the prefix E (for example, 79E125).

Field experiments. In the experimental field nursery of the Kazakh Research Institute of Agriculture and Plant Growing (N43°13'09" E76°41'17"), experiments were conducted to study the resistance of wheat varieties and lines to yellow rust. For this purpose, the seeds of Yellow Rust Trap Nursery (YRTN, CIMMYT) were sown, including Avocet isogenic Yr lines (Figure 1). Sowing was carried out using the standard method (1-meter row with a distance between rows of 20 cm). The Morocco variety, a spreader row of infection, was used as a susceptible indicator. Seeds of this variety were sown every 20 rows to ensure the uniform spread of yellow rust infection. Inoculation of the studied genotypes was carried out with a *Pst* population (dominant races 79E125, 79E27, 79E155 and others) with talc in a ratio of 1:100, with a load of 20 mg of spores/m^2. The inoculum of the *Pst* population was a mixture of uredospores from a local population of the fungus previously collected from wheat crops in the experimental area. The first assessment of the development of the disease was carried out at the beginning of its manifestation, followed by subsequent ones, with an interval of 7–10 days until the milky-waxy ripeness of the grain. The main phytopathological parameters for assessing genotypes for resistance to the yellow rust pathogen were Infection Type (IT) and degree of damage (%). The type of infection was determined using the recommended CIMMYT score (Roelfs et al.1992): resistant (R), moderately resistant (MR), moderately susceptible (MS), and susceptible (S). The degree of damage (%) of plants was determined using the modified Cobb scale (Peterson et al. 1948). The coefficient of infection (CI) for yellow rust development was calculated by multiplying the constant values of infection types by the degree of susceptibility. Constant values of infection types were used: $I = 0.0$; $R = 0.2$; MR = 0.4; $M = 0.6$; MS = 0.8; and $S = 1.0$ (Stubbs et al. 1986).

RESULTS

Collection *Pst* races. 1985–2010, of the 46 differentiated races of the *Pst* pathogen, the most virulent 10 races were widespread on winter wheat varieties (60.0–80.0%). The studied *Pst* races were predominantly virulent to the differentiating varieties from the International and European sets: Vilmorin 23, Heines Kolben, Lee, Chinese 166, Heines VII, Compair, Nord Desprez, Heines Peko, Reichersberg 42, Hybrid 46. Race 31E159 was virulent to the Moro variety, and 47E224 – to Spaldings Prolific. All races were virulent to Heines Kolben, Lee, Chinese 166, Heines VII, Reichersberg 42 (Figure 2).

According to the dynamics of change and the frequency of occurrence of *Pst* races from 1985

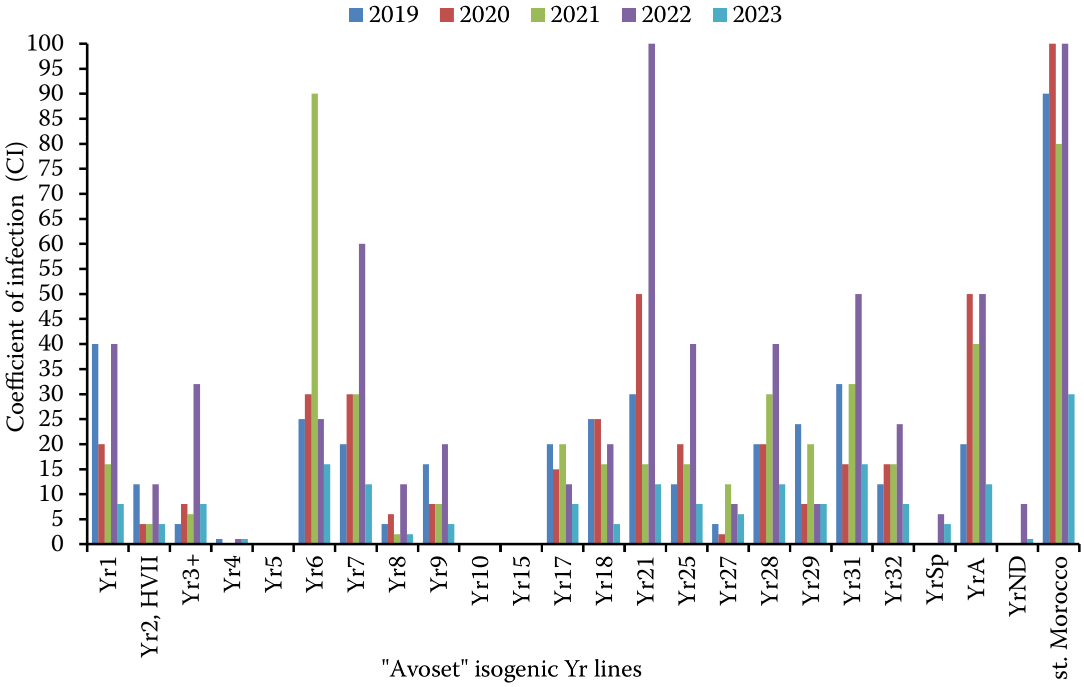

Figure 1. Effectiveness of Yr genes against the *Pst* population in Kazakhstan

Almalybak population dominant races 79E125, 79E27 and 79E155

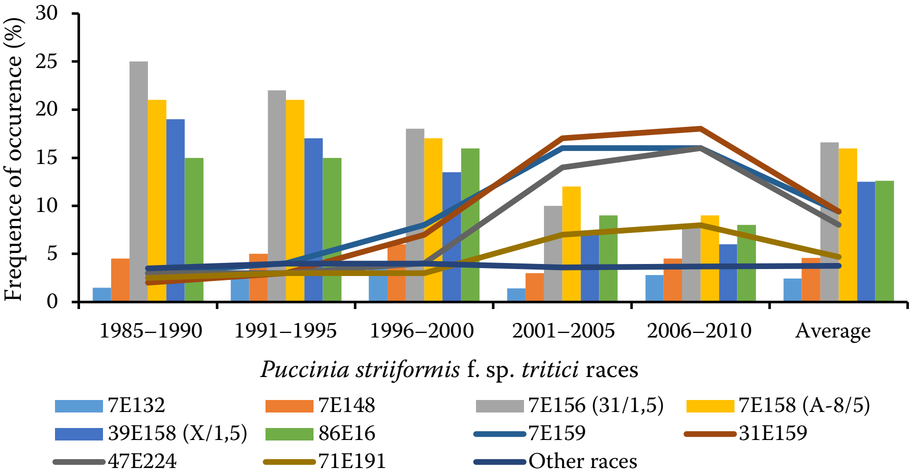

Figure 2. *Puccinia striiformis* f. sp. *tritici* races on winter wheat in Kazakhstan during 1985–2010

to 2010, the data are grouped by 5-year periods. From 2001 to 2010, changes occurred in the racial composition; the occurrence of races 47E224, 7E159, 71E191, and 31E159 is significantly higher (lines in Figure 2 show data) than in previous years.

15-year period (1985–2000) in the southeast of Kazakhstan, the main *Pst* races were 7E156 (31/1.5), 7E158 (A-8/5), 39E158 (X /1.5) and 86E16. These races formed the basis of the population of yellow rust on winter wheat (73.2%), while during the specified period, the average occurrence of race 7E156 (31/1.5) was 21.7%, 7E158 (A-8/5) – 19,7%, 39E158(X/1.5) – 16.5%, 86E16 – 15.3%. However, since 2001, the region has seen a change in the racial composition of the pathogen. Races 7E159, 31E159, and 47E224, whose occurrence was previously within 3%, began to predominate in the *Pst* population. Structural analysis of the population in 2001–2005 and 2006–2010 showed that the average occurrence of race 7E159 was 16%, race 31E159 – 17.5%, and race 47E224 – 15%. Although the average occurrence of the latter races over the 25 years (1985–2010) is 8.0–9.4%, the increase in their frequency of occurrence for 2001–2010 shows a change in the racial composition of the causative agent of the disease. In addition, in the southeast of Kazakhstan in 2002, 2003 and 2005. Favourable weather conditions contributed to the strong development of yellow rust on susceptible winter wheat varieties.

New *Pst* isolates. In 2018, 2019 and 2022, moderate development of yellow rust was observed in the foothill grain-growing areas of the southeast of the republic. In recent years, monitoring studies have been repeatedly carried out to determine the development of diseases and the collection of samples of yellow rust for subsequent determination of the composition of the population. Yellow rust was examined on wheat crops in 3 regions of Kazakhstan (Almaty, Zhambyl, Turkestan). The disease developed to an average extent in crop production in the Kordai and Zhualinsky districts of the Zhambyl region and the Karasai district of the Almaty region. In contrast, the degree of disease development in susceptible varieties was 30–40%. Observations of the phytosanitary condition of wheat crops over three years revealed that the development and spread of diseases vary depending on the cultivated variety, as well as the year and region where the research is conducted in Kazakhstan (Rsaliyev et al. 2023). And in 2020, 2021, and 2023, due to drought in the region, there was no maximum development of grain crop diseases, including yellow rust. The complete absence or weak development of the disease was noted on the crops.

The collected samples of yellow rust in 2018, 2019 and 2022 in the southeast of Kazakhstan were transferred to the Institute of Biological Safety Problems, where an analysis of the *Pst* population on differentiator varieties was carried out, and their virulence on isogenic Yr lines was determined. To determine the *Pst* races of wheat, 145 *Pst* isolates were used, among which 123 viable mono pustule isolates were used for experiments. Analysis of the studied isolates revealed the presence of 28 races of the fungus on winter wheat in the population (Table 1).

As a result of the analysis of the *Pst* population from the Almalybak area, 16 races of the pathogen were isolated from 48 isolates, which is much more compared to other areas where from 2 (Kainar) to 8 races (Aspara and Rgayty) were isolated.

As the data in Table 1 shows, in the south and southeast of Kazakhstan in 2018–2022, the main dominant *Pst* races were 7E159, 39E158, 66E35,

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Table 1. Characteristics of *Puccinia striiformis* f. sp. *tritici* races of wheat in the southern regions of Kazakhstan in 2018–2022

Race code*	Reaction of differentiating varieties															Proportion of virulence (%)	Number of isolates in populations						Frequency of occurrence (%)
	International set							European set															
	Suwon 92/Omar (YrSu92)	Strubes Dickkopf (Yr25)	Moro (Yr10, YrMor)	Vilmorin 23 (Yr3a, Yr4a)	Heines Kolben (Yr6)	Lee (Yr7)	Chinese 166 (Yr1)	Heines VII (Yr2)	Spaldings Prolific (YrSp)	Carstens V (Yr32)	Compare (Yr8, YrCom)	Nord Desprez (Yr3a; Yr4a)	Heines Peko (Yr6, Yr2)	Reichersberg 42	Hybrid 46 (Yr3b)		Almalybak	Betkainar	Rgaity	Kainar	Talapty	Aspara	
7E159	A**	A	A	A	V***	V	V	V	A	A	V	V	V	V	V	60.0	4	2	2	0	2	0	8.1
39E158	A	V	A	A	V	V	V	V	A	A	V	V	V	V	A	60.0	4	2	0	0	0	2	6.5
79E73	V	A	A	V	V	V	V	A	V	A	A	V	A	A	V	53.3	2	3	0	0	3	0	6.5
79E187	V	A	A	V	V	V	V	V	A	V	V	V	A	V	V	73.3	0	0	0	3	2	3	6.5
66E35	V	A	A	A	A	V	A	A	A	V	A	A	A	V	V	33.3	4	2	0	0	0	0	4.9
15E159	A	A	A	V	V	V	V	V	A	A	V	V	V	V	V	66.7	3	0	0	0	2	0	4.1
31E158	A	A	V	V	V	V	V	V	A	A	V	V	V	V	A	66.7	0	0	2	0	0	3	4.1
47E223	A	V	A	V	V	V	V	V	V	A	V	V	V	V	V	80.0	3	2	0	0	0	0	4.1
79E43	V	A	A	V	V	V	V	A	A	V	A	V	A	V	V	60.0	0	0	0	0	5	0	4.1
79E143	V	A	A	V	V	V	V	V	A	A	A	V	V	V	V	66.7	0	0	0	0	0	5	4.1
79E179	V	A	A	V	V	V	V	V	A	V	V	A	A	V	V	66.7	0	0	0	0	0	5	4.1
111E158	V	V	A	V	V	V	V	V	A	A	V	V	V	V	A	73.3	3	0	2	0	0	0	4.1
75E41	V	A	A	V	A	V	V	A	A	V	A	V	A	A	V	46.7	0	2	2	0	0	0	3.3
77E137	V	A	A	V	V	A	V	V	A	A	A	V	A	A	V	46.7	0	0	0	4	0	0	3.3
79E8	V	A	A	V	V	V	V	A	A	A	A	V	A	A	A	40.0	4	0	0	0	0	0	3.3
79E25	V	A	A	V	V	V	V	A	A	A	V	V	A	A	V	53.3	4	0	0	0	0	0	3.3
79E27	V	A	A	V	V	V	V	A	A	A	V	V	A	V	V	60.0	4	0	0	0	0	0	3.3
79E104	V	A	A	V	V	V	V	A	V	V	A	V	A	A	A	53.3	2	0	2	0	0	0	3.3
79E152	V	A	A	V	V	V	V	V	A	A	V	V	A	A	A	53.3	1	0	0	0	0	3	3.3
2E9	A	A	A	A	A	V	A	A	A	A	A	V	A	A	V	20.0	3	0	0	0	0	0	2.4
7E155	A	A	A	A	V	V	V	V	A	A	V	V	A	V	V	66.7	2	0	1	0	0	0	2.4
79E155	V	A	A	V	V	V	V	V	A	A	V	V	A	V	V	66.7	3	0	0	0	0	0	2.4
71E9	V	A	A	A	V	V	V	A	A	A	A	V	A	A	V	40.0	0	0	2	0	0	0	1.6
71E209	V	A	A	A	V	V	V	V	V	A	V	A	A	A	V	53.3	0	0	2	0	0	0	1.6
77E170	V	A	A	V	V	A	V	V	A	V	A	V	A	V	A	53.3	2	0	0	0	0	0	1.6
103E35	V	V	A	A	V	V	V	A	A	V	A	A	A	V	V	53.3	0	0	0	0	0	2	1.6
111E32	V	V	A	V	V	V	V	A	A	V	A	A	A	A	A	46.7	0	2	0	0	0	0	1.6
75E73	V	A	A	V	A	V	V	A	V	A	A	V	A	A	V	46.7	0	0	0	0	0	1	0.8
No. of *Pst* races from the area																	16	7	8	2	5	8	

*Races ranked by frequency of occurrence in regions; **A – avirulence; ***V – virulence

79E73 and 79E187, in which the frequency of occurrence in the population was in the range of 4.9–8.1%.

The studied populations of Almalybak, Rgayty and Aspara varied in racial composition. Thus, races 2E9, 77E170, 79E8, 79E125, 79E27 and 79E155 were registered in the Almalybak population, races 71E9 and 71E209 were found only in the Rgayty population, and races 75E73, 79E143 and 79E179 were identified in the Aspara population. The most dangerous races in the region are 7E155, 15E159, 31E158, 47E223, 79E143, 79E155, 79E179, 79E187 and 111E158, whose virulence to yellow rust-differentiating varieties was 66.7–80.0% of the races. Many *Pst* races show virulence to the differentiating varieties Chinese 166 (26 races out of 28, or 92.8%), Lee (26 races, 92.8%), Heines Kolben (24 races, 85.7%), Nord Desprez (23 races, 82.1%), Suwon92/Omar (21 races, 75%), Vilmorin 23 (20 races, 71.4%), Hybrid 46, (20 races, 71.4%), Reichersberg 42 (16 races, 57.1%), Heines VII (15 races, 53.6%), Compare (14 races, 50%), Heines Peko (7 races, 25%). Only one race (31E158) showed virulence to the variety Moro; also, races 47E223, 71E209, 75E73, 79E73, and 79E104 overcame the resistance of the variety Spaldings Prolific. Under the conditions of Kazakhstan, all races were avirulent to the Yr5 source.

Using isogenic Yr lines of the Avocet variety, the virulence of the predominant *Pst* races in Kazakhstan in 2018–2022 was determined. At the same time, data on the damage to Yr lines are written as a virulence formula, indicating effective resistance genes at the beginning and ineffective genes through the line. By processing the results of damage to isogenic lines, we determined the proportion of Yr genes that are effective and ineffective for each *Pst* race (Table 2).

The data in Table 2 confirmed the results of differentiation of *Pst* races, in particular, races with high virulence to differentiator varieties also turned out to be virulent to isogenic Yr lines. The proportion of Yr genes susceptible to new races ranged from 31.25–68.75%. It should be noted that many new *Pst* races overcome not only known ineffective genes (Yr1, Yr6, Yr7, Yr8, Yr11, Yr12, Yr17), but also individual effective resistance genes (Yr9, Yr15, Yr18, Yr24, Yr26, Yr27). Thus, out of 12 new races, 9 showed virulence to the Yr18 line, 7 to Yr26, 5 races – to Yr27. Of great interest for wheat breeding for immunity are races 7E159 and 31E158, which overcome the effective resistance gene Yr9, and races 15E159 and 79E187, which are virulent for the Yr15 gene. Thus, using these races to test breeding material in greenhouse conditions allows the creation of varieties resistant to yellow rust. It is proposed to use races virulent to isogenic lines Yr9, Yr15, Yr18, Yr24, Yr26, and Yr27 to breed race-specific resistance in controlled conditions.

***Pst* population in the field.** Using isogenic Yr lines, the virulence of the predominant *Pst* races in Kazakhstan in 2018–2022 was determined by reaction to differentiating varieties. At the same time, data on the damage to Yr lines are written as a virulence formula, indicating effective resistance genes

Table 2. Virulence of the predominant *Puccinia striiformis* f. sp. *tritici* races to Yr lines

Race code*	Virulence formula (resistance/susceptible)	Proportion of Yr genes (%)	
		R	S
15E159	Yr5, 9, 10, 24, Sp / 1, 6, 7, 8, 11, 12, 15, 17, 18, 26, 27	31.25	68.75
7E159	Yr5, 10,15, 24, 26, Sp / 1, 6, 7, 8, 9, 11, 12, 17, 18, 27	37.50	62.50
79E187	Yr5, 9, 10, 24, Sp, 27 / 1, 6, 7, 8, 11, 12, 15, 17, 18, 26	37.50	62.50
47E223	Yr5, 9, 10, 15, 17, Sp, 27 / 1, 6, 7, 8, 11, 12, 18, 24, 26	43.75	56.25
79E73	Yr5, 9, 10, 15, 24, 26, Sp / 1, 6, 7, 8, 11, 12, 17, 18, 27	43.75	56.25
79E179	Yr5, 9, 10, 15, 24, 26, Sp / 1, 6, 7, 8, 11, 12, 17, 18, 27	43.75	56.25
111E158	Yr5, 9, 10, 15, 24, 26, Sp / 1, 6, 7, 8, 11, 12, 17, 18, 27	43.75	56.25
31E158	Yr5, 7, 10, 12, 15, 24, Sp, 27 / 1, 6, 8, 9, 11, 17, 18, 26	50.00	50.00
79E43	Yr5, 9, 10, 15, 18, 24, Sp, 27 / 1, 6, 7, 8, 11,12, 17, 26	50.00	50.00
79E143	Yr5, 7, 9, 10, 12, 15, 24, 26, Sp, 27 / 1, 6, 8, 11, 17, 18	62.50	37.50
39E158	Yr5, 6, 7, 9, 10, 11, 15, 17, 18, 24, Sp, 27 / 1, 8, 12, 26	75.00	25.00
66E35	Yr5, 8, 9, 10, 11, 12, 15, 17, 18, 24, Sp, 27 / 1, 6, 7, 26	75.00	25.00
Averaged data		49.32	50.68

*Races ranked by virulence to Yr lines; **R – resistance; ***S – susceptible at the beginning and ineffective genes through the line. By processing the results of damage to isogenic lines, we determined the proportion of Yr genes that are effective and ineffective for each *Pst* race (Table 2).

Field studies conducted in 2019–2023 at the Kazakh Research Institute of Agriculture and Plant Growing (N43°13'09", E76°41'17") with the maximum development Coefficient of Infection (CI) in the Morocco variety showed the effectiveness of individual Yr genes against the local *Pst* population in the adult stage. Against an infectious background, isogenic lines Yr5, Yr10, and Yr15 retained their reliability in resisting the *Pst* population in Kazakhstan. During the five-year field study, the sources Yr2 (average CI = 7.2), Yr4 (0.6), Yr8 (5.2), Yr27 (6.4), YrSp (2.0), YrND (1.8) also had high efficiency. It should be added that in the region, the strongest development of yellow rust and other diseases of airborne infection was in 2022 when high infection rates were noted for Yr1 (CI = 40), Yr7 (60), Yr21 (100), Yr25 (40), Yr28 (40), Yr31 (50), YrA (50) and Morocco (100) (Figure 1).

DISCUSSION

Despite the complexity of processing the results, the standard *Pst* race differentiation method (Johnson et al. 1972) is currently used in many countries, including Kazakhstan. Using this method, a total of 28 *Pst* races were identified in the southeast of the republic in 2018–2022, including 16 races from Almalybak, 7 races – Betkainar, 8 races – Rgaity, 2 races – Kainar, 5 races – Talapty and 8 races from Aspara. The identification of 16 *Pst* races in the Almalybak area is explained by the fact that the Kazakh Research Institute of Agriculture and Plant Growing is located here, where various varieties of grain crops are cultivated (bread and durum wheat, triticale, barley), on which a frequent race-forming process may occur. Among them, races 7E159, 39E158 and 79E187 were found in early studies in Kazakhstan (Kokhmetova et al. 2018). These races formed the basis of the synthetic yellow rust population when determining wheat varieties' resistance against an infectious background.

In recent years, in the south and southeast of Kazakhstan, as well as throughout Central Asia and the Caucasus, where winter wheat is mainly cultivated, yellow rust has become one of the main diseases (Kokhmetova et al. 2018; Koyshybaev 2018; Dubekova 2021). The expansion of winter wheat acreage in Uzbekistan and Tajikistan, where winters are milder and good overwintering of the yellow rust pathogen on seedlings is possible, has noticeably aggravated the phytosanitary situation in the region (Sharma et al. 2013). At the beginning of 2000, a strong development of the disease was observed in the mountainous zone of the Almaty region, as well as on irrigated lands in the Turkestan and Zhambyl regions. In 2002, an epidemic of the disease was noted in the south and southeast of the republic; many commercial varieties of winter wheat (Steklovidnaya 24, Bogarnaya 56, Karlygash and others) were 75–100% affected in the flag leaf phase (Morgounov et al. 2012; Koyshybaev 2018). At the same time, the development of the disease in the well-known commercial variety Bezostaya 1 was in the range of 20–40%. The development of diseases in the winter wheat variety Bezostaya 1 was studied in many international nurseries and more than 50 countries from 1969 to 2010. As a result, stable long-term resistance of the Bezostaya 1 variety to types of rust and powdery mildew was established. The genotype of the Bezostaya 1 variety contains a set of resistance genes Lr34/Yr18/Pm38, which is currently an important target for breeding (Morgounov et al. 2012).

In Central and East Asia and North African countries from 2002 to 2011 (Jamil et al. 2020), there was a pandemic of yellow rust from wheat. This was stated by the participants of the International Symposium on Yellow Rust of Wheat, held on April 18–20, 2011, at ICARDA (Aleppo, Syria). The following four factors contributed to the region's development and spread of yellow rust. First, cultivating genetically homogeneous varieties over a large area (mega varieties) created favourable genetic conditions for *Pst*. For example, in India, only one variety, PBW343, is zoned over 6 mil. ha; in Pakistan, the variety Inqualab 91 is sown on 5 mil. ha (Rehman et al. 2013). Secondly, the traditional farming culture in the region allows for a "green bridge" to develop the yellow rust pathogen (Yahyaoui 2003). Thirdly, the region is experiencing gradual climate change. In East Asia and North Africa, winter has become warmer and wetter, facilitating the persistence and development of infection in winter wheat and cereal grasses. The last fourth factor is a change in the racial composition of the pathogen with the formation of virulent pathotypes. A feature of the new *Pst* races of the last decade is their virulence towards varieties with the Yr27 gene (Cham8, Chamran, Inquilab 91, Kubsa, PBW 343). A similar case was noted in 1999–2003 when wheat varieties with the Yr9 gene (Dashen, Falat, Mexipak, Pak 81, Seri 82) were susceptible to the disease. Thus, it can be stated that *Pst* races virulent to Yr9 and Yr27 circulate in the natural environment, respectively; using these genes in breeding programs is ineffective.

Geographical patterns of pathogen development characterize studies on genetically diverse *Pst* populations and their virulence. In Turkey, most of the collected isolates were virulent with varying frequencies of resistance genes Yr1 (50%), Yr6 (100%), Yr7 (78%), Yr8 (50%), Yr9 (84%), Yr10 (25%), Yr17 (38%), Yr24 (22%), Yr27 (31%), Yr32 (22%), Yr43 (47%), Yr44 (6%), YrSp (41%), YrTr1 (6%) and avirulent on Yr5 and Yr15. Based on virulence analysis, all isolates were identified into 25 races and grouped into six virulence groups (Cat et al. 2021). Subsequently, 38 *Pst* races, including 25 not previously reported, were identified from 140 isolates obtained from most regions of Turkey between 2018 and 2020 using a differential set containing 18 wheat lines with a single Yr gene (NIL) Avocet. Virulence to Yr15 was not observed among any of the isolates. Virulence to the remaining 17 Yr genes was detected at various frequencies. The frequencies of virulence to Yr6, Yr9, Yr7, Yr8, Yr43, YrExp2, Yr44, YrTr1, and Yr27 were high (57.1–100.0%), to Yr1, Yr17, Yr32, and YrTye were moderate (24.3–42.9%), and to YrSP, Yr24, and Yr10 were low (9.3–17.1%). Only one race was virulent to Yr5 (0.7%). Many of the races identified were common among regions, indicating that *Pst* races migrate throughout Turkey (Cat et al. 2023).

In China, differentiation of *Pst* races has been carried out on a large scale since 1950 using its methods. So far, more than 34 races of the fungus have been identified in the country, which is designated CYR1–CYR34 (Chinese Yellow Rust) (Wan et al. 2007; Zeng et al. 2022). After 2000, varieties with Yr26, including Yr10 and many others, were overcome by the CYR34 (formerly G22-9) race (Liu et al. 2010). In the country, high-temperature resistant wheat varieties have been isolated that show resistance to the aggressive race of yellow rust CY29 against an infectious background (Ma & Shang 2004). Recently, a new race virulent to Yr5 was discovered, which shows that this gene's use in wheat breeding is not promising (Zhang et al. 2020).

In India and Pakistan after 2000, the emergence and movement of avirulent Yr27 race posed a serious threat to wheat production, where the mega cultivars PBW 343 and Inqilab 91 had Yr27-based resistance. In 2005, the wheat crop in Northern Pakistan was severely affected by this *Pst* race, where most of the area was under the Inqilab 91 variety (Rehman et al. 2013). A study was conducted in Pakistan in 2018–2019 to identify the virulence patterns of yellow rust and the prevalence of dominant races. Virulence analysis identified 8 *Pst* races from the samples analyzed, with race 564200 being the most common race among these races, followed by 574201 and 574200. The remaining races, including 574210, 564202, 560200, 574232, and 164200, accounted for 6.66% of all races identified. No virulence was found for Yr5, Yr10, Yr15, Yr24, Yr32, YrSp and YrTye, while all isolated races were found to be virulent to genes including Yr1, Yr8, Yr9 and Yr27 (Sufyan et al. 2021).

Similar studies have been conducted in Australia (Wellings 2007, 2011), Iran (Hosni et al. 2003; Omrani et al. 2018) and other countries. In European countries, at least three races of non-European origin, termed 'Warrior', 'Kranich' and 'Triticale aggressive', were identified in the post-2011 population. The presence of new *Pst* races in the European population in the first year of detection and across large areas is consistent with a hypothesis of aerial spread from genetically diverse source populations (Hovmøller et al. 2016). In the North Caucasus region of Russia, since 1990, there has been a steady tendency to expand the range of the yellow rust pathogen. Even in conditions unfavourable for the pathogen, the disease is recorded in the region every year. In some areas, there are foci of the disease with damage of up to 50%. No isolates virulent to lines carrying the Yr3, Yr5, Yr26, or YrSp genes were found in the population. The frequency of *Pst* isolates virulent to lines with Yr genes: 4+12, 6, 7+25, 7, 8, 2+HVII, 32, 2+9, 3a+4a+ND, SD varies from 6 to 19% (Volkova et al. 2020). In recent years, whet yellow rust has appeared in Western Siberia, particularly in Novosibirsk and Krasnoyarsk (Gultyaeva et al. 2022), which may be due to climate warming in the region, since the causative agent of the disease, except in individual cases, was not previously detected in Northern Kazakhstan and Western Siberia (Koyshybaev 2018).

In Uzbekistan, this disease has also become widespread in wheat since 2000. High infestation of crops was noted in Surkhandarya, Tashkent and Syrdarya regions. By 2003, 4 races were identified in Uzbekistan, three previously noted in Central

Asia (Khokhlacheva & Khasanov 2003). Despite establishing an alternative host for yellow rust (Jin et al. 2010) in Central Asia, the role of barberry species in the life cycle and the pathogen's race-forming process has not yet been studied.

In the natural environment, individual virulent races appear among the non-predominant races in the pathogen population. Thus, in America, the virulence genes Yr17, Yr27, Yr32, Yr43, Yr44, YrTr1 and YrExp2 appeared 14–37 years earlier than previously reported (Liu et al. 2017). Similar research was conducted in our studies. Since 2001, severe yellow rust epidemics have occurred in Kazakhstan as a result of changes in the racial composition of the pathogen. Races 7E159, 31E159, and 47E224, whose occurrence was previously within 3%, began to predominate in the population, and their average occurrence was within 15–17.5%. Such "long-live races" form the basis of virulence in the *Pst* population in Kazakhstan. Our data do not agree with the results of Hubbard et al. (2015) in the United Kingdom, where new *Pst* isolates are not associated with an older population due to the emergence of virulent *Pst* races, quickly dislodging the previous population.

Thus, an analysis of the literature and our research on the population composition of yellow rust shows that in Central Asia Transcaucasia and other regions, new races of this fungus are often found on wheat. The migration of spores from the areas of population formation and the spread of virulent races to commercial varieties create a dangerous epidemic in these regions. The yellow rust population study results in Kazakhstan in 1985–2022 allow us to identify three periods with characteristic dominant *Pst* races. The first period covers 1985–2000, when in the southeast of the country, the main types of yellow rust were 7E156 (31/1.5), 7E158 (A-8/5), 39E158 (X/1.5) and 86E16. In the second period (2001–2010), the crops were dominated by races 7E159, 31E159 and 47E224, which showed virulence to varieties with resistance genes Yr9 and Yr18. In the third period (2018–2022), the most dominant races in the *Pst* population were 7E159, 39E158, 79E73, 79E179, and 111E158, which showed virulence to varieties with the Yr26 and Yr27 genes. Against the background of field infection, the resistance genes Yr5, Yr10, and Yr15 remain reliable in ensuring resistance; the sources of the genes Yr4, YrSp and YrND are also highly effective against the *Pst* population. In production, varieties that combine race-specific resistance with field (APR) non-specific resistance should be of great practical importance. Donors of field resistance can carry in their genotype at least one APR gene with a field resistance effect, which can be closely linked to minor, durable genes (Lagudah et al. 2009). Annual immunological studies show that yellow rust increases in genotypes previously noted for resistance, except in dry years. The last two decades have witnessed the rapid global emergence of more aggressive and genetically diverse *Pst* populations adapted to higher temperatures (Hovmøller et al. 2016). In this regard, to enhance the selection of rust-resistant varieties, it is important to use highly effective and efficient genes – sources of resistance.

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