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Cereal breeding for biotic stress resistance in Martonvásár

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Abstract: The objectives of this study were to examine the resistance of cereal varieties and lines under field conditions near Martonvásár during the 2022/2023 and 2023/2024 growing seasons. The two studied seasons were characterized by the dominance of different rust diseases. In the first period, a very strong yellow rust epidemic, while in the second period, a leaf rust outbreak provided a good opportunity for selecting resistant lines. Leaf spot pathogens were continuously present in the cereal fields during the examined vegetation periods. After microscopic examination, several leaf spot pathogens were identified, including *Pyrenophora* species, Septoria leaf blotch, caused by the fungus *Zymoseptoria tritici* (formerly known as *Septoria tritici* or *Mycosphaerella graminicola*), the pathogen of glume blotch (*Parastagonospora nodorum*), as well as *Fusarium* and *Alternaria* species, along with a bacterial infection. Cereal varieties and lines with good resistance and tolerance were identified in both growing seasons. Observations from the 2022/2023 and 2023/2024 growing seasons reinforce the long-standing experience that, besides the characteristics of the growing season, resistance of varieties plays a crucial role in disease management and successful cereal production. Within the European Union's "Green Deal," the "Farm to Fork" strategy emphasizes the goal of reducing pesticide use by 50% by 2030. Breeding of resistant cultivars is the most economic and eco-friendly method to control plant diseases. The development of high-yielding, high quality, as well as disease-resistant varieties has always been a priority in the breeding programs in Martonvásár.

Keywords: cereals; leaf rust; yellow rust; breeding; pathogens

INTRODUCTION

Resistance to various diseases is a fundamental factor for the safe cultivation of cereals. Worldwide, wheat is threatened by 200-250 pathogens and pests (Wiese, 1987), of which approximately 5-10 diseases occur more frequently in Hungary and can even cause substantial economic damage

in commercial cultivation. This can be as high as 20-80% in susceptible varieties (Mourad et al., 2024). By growing varieties resistant to these pathogens, the amount of pesticides applied can be reduced, thus producing less chemical residue-containing food and raw material with less environmental pollution and at a lower cost.

Although it had appeared sporadically before, the first epidemic of wheat powdery mildew was observed in 1961 (Podhradszky and Csuti, 1962). Since then, natural infections have been occurred each year. Both the composition of races and the fluctuations in powdery mildew populations have been studied in our institute since 1971. Our results revealed that none of the major genes are capable of conferring full resistance against powdery mildew. Severe infection (virulence>90%) was detected in all wheat varieties carrying resistance genes *Pm2*, *Pm3c*, *Pm4a*, *Pm5*, *Pm6* or *Pm8*. Through the consistent breeding methods however, the majority of wheat varieties bred in our institute carry such resistance against powdery mildew that, under average growing conditions, they are either not affected or only mildly infected (Vida et al., 2007).

Rust infections still pose a serious threat to cultivated wheat. Among the three most widespread rust species (brown or leaf; stem or black and yellow or stripe rust), leaf rust currently appears to be the most prevalent. Stem rust was a regular occurrence until the 1970s, however, due partly to the success of targeted wheat breeding programs, it has been almost entirely eradicated from Hungary. Nevertheless, the climate in Hungary is also favorable for this pathogen and may become even more so due to global warming. This is because the optimum temperature for stem rust reproduction is higher, than those of the other two rust species (Roelfs et al., 1992). With the emergence of the Ug99 race – also known by the North American nomenclature as TTKSK – the threat of stem rust re-emergence may be increased, as it can cause a susceptible reaction (i.e., it is virulent) even in wheat varieties carrying the resistance gene *Sr31* (Pretorius et al., 2000). Several wheat varieties bred in Martonvásár carry this resistance gene (Purnhauser et al., 2011). New, virulent in lineages of the race Ug99 have been evolved (Singh et al., 2015). The third major rust species, stripe or yellow rust, that has been common in Western-European countries, has caused severe epidemics since its first unusually strong appearance in 2014 (Vida et al., 2014a.).

These pathogens of major importance can cause varying degrees of yield loss depending on the susceptibility of the host plant. Data obtained in Hungary show that wheat powdery mildew can reduce yield by 2–20%, leaf rust by 2–30%, and stem rust by 5–40% (Szunics and Szunics, 2010). Depending on the season, different fungal species causing leaf spot infections can lead to economically significant damage. Although these pathogens have been known for a long time (Mezey, 1899; Eyal et al., 1987), they have only gained increased attention in recent decades. Besides quantitative and qualitative damage they cause, visual identification of these pathogens is challenging, which further complicates effective control.

Symptoms caused by the pathogens vary what makes their classification less straightforward than that of the biotrophic species. Along with the most common fungi species causing leaf spot symptoms [*Pyrenophora tritici-repentis* (Died.) Drechs. (anamorph: *Drechslera tritici-repentis*), *Phaeosphaeria nodorum* (E. Müll.) Hedj. (anamorph: *Stagonospora nodorum* (Berk.), *Mycosphaerella graminicola* (Fuck.) (anamorph: *Zymoseptoria tritici* Rob. ex Desm.), *Cochliobolus sativus* (S. Ito & Kurib.) (anamorph: *Bipolaris sorokiniana* (Sacc.))]. Other pathogens such as other fungi species, viruses, bacteria, genetic, physiological causes and abiotic stress factors can also cause similar symptoms. Of the two most common fungi species, *P. tritici-repentis* and *Z. tritici* can also cause 50% yield loss (Murray et al., 1998; Eyal et al., 1987).

In Hungary, winter barley is the second most widely cultivated species, with a sowing area exceeding 285,000 ha in 2024 (Hungarian Central Statistical Office, 2025). The main diseases of barley are powdery mildew, dwarf leaf rust and barley net blotch. The scale of damage varies depending on the pathogen, ranging from 1.2 to 50% (Murray et al., 2013).

The aim of this study were 1) to determine the dominance of pathogens occurring in the different management systems during the two growing seasons, 2) to evaluate the resistance of cereals to the most important pathogens, 3) to detect the

ideal wheat genotype under different management systems in the two epidemic years.

MATERIALS AND METHODS

Field experiments

Field trials were set up in 2022/2023 and 2023/2024 growing seasons to assess resistance/susceptibility of winter cereal varieties and breeding lines (wheat, durum wheat, triticale and barley) bred in Martonvásár under low-input, Lászlópuszta (LP) and conventional, Martonvásár (MV) management systems in Martonvásár (47°3'N, 18°8'E), Hungary.

The conventional treatment used the same agronomic practices and fertilization regime as the neighboring farmers, the low-input treatment used 50% less fertilization. The soil type in the experimental fields was a chernozem with forest residues and its shallow layer did not contain lime and harmful salts. This layer had a neutral pH (pH = 7.0/6.7; LP /MV) and, in terms of its physical properties, it was loam. Based on its humus content (2.4/3.0 m/m%), it had a moderate nitrogen supply, the phosphorus content was medium (114/134 mg kg⁻¹), the potassium supply was good (314/295 mg kg⁻¹). In terms of microelements, zinc content of the soil was less than optimal (1.1/1.3 mg kg⁻¹), while copper (2.7/3.5 mg kg⁻¹) and manganese (156/208 mg kg⁻¹) contents were sufficient. The 6 m² trial plots (row distance 0.15

m) were machine-drilled (HEGE-80 drill; Hans-Ulrich Hege GmbH & Co., Waldenburg, Germany) at optimal fall sowing date. The experiments were combine-harvested (Wintersteiger Nursery Master Elite; Wintersteiger AG, Ried, Austria) at full maturity. No fungicides were applied, but plots were treated with herbicide and insecticide, whenever it was needed.

Weather conditions

During the two growing seasons, more similarities in weather conditions were observed, which were different from the thirty-year average. All two growing seasons were characterized by a mild winter. In all two years, the mean temperature between October and March was often above than the thirty-year average (Table 1). According to Hungaromet's summary (www.met.hu), the winter and spring in the 2023/2024 growing season were the warmest in the climate data series written since 1901. Moreover, according to a report by the World Meteorological Organization (WMO; www.wmo.int), after 2023, 2024 was also the warmest year globally since 1850.

The amount of precipitation in Hungary exceeded the long-term average in 2023, and in the following year, the amount of precipitation approached the 30-year average, but most of the location of our country was characterized by a deficit during the season. Most of the precipitation in Martonvásár arrived in the autumn-winter months in both growing seasons, the amount



Image 1. Necrosis on the leaf surface against to yellow rust (Martonvásár 2023)

Table 1. Monthly average precipitation and temperature in the two cereal growing seasons (2022-2023 and 2023-2024) and long-term meteorological data at the experimental locations (Martonvásár, Hungary)

2022/2023										2023/2024				
Precipitation (mm)				Temperature (°C)				Temperature (°C)						
Mean of 30 years	2002/2023	2023/2024	Mean of 30 years	Mean	Max	Min	No. of below freezing days*	No. of heat days**	Mean	Max	Min	No. of below freezing days*	No. of heat days**	
October	36.3	2.5	52.4	11.8	12	21.9	-1.3	1	13.8	28.2	-1.9	2		
November	52.2	49.6	92.3	5.7	6.7	19.2	2.9	0	6.1	18.7	-5.4	12		
December	43.1	63.1	114	1.6	2.1	12.7	-6.8	17	2.1	11.4	-8.4	19		
January	35.5	112.7	26.9	0.6	3.9	14.6	-6.2	11	1.5	11.9	-9.3	22		
February	28.8	13.5	32.1	2.2	3.2	16.9	-11	14	7.8	18.5	-4.1	8		
March	31.5	39.5	21	6.7	7.3	23.1	-5.8	14	9.1	25.5	-4.0	6		
April	37.9	18.3	19.4	12.3	9.8	22.5	-4.9	4	12.8	28.5	0.5			
May	59.6	60.3	66.4	17.3	16.2	28.4	3.1		17.7	27.7	4.9			
June	64.9	70.5	59	20.2	20	33	9.2	5	21.3	35.2	9.4	6		
July	45.3	29.1	1.6	22.4	23.1	34.8	11.8	12	24.9	37.6	10.2	22		
Σ***	435.2	459.1	422.3	100.8	104.3	227.1	-9.0	61	117.1	243.2	-8.1	69	28	

Notes: * Daily minimum temperature ≤ 0°C; ** Daily maximum temperature ≥ 30°C; *** period from sowing to harvest

of precipitation between March and May was around the average in 2023, while in 2024 it was below the thirty-year average

Disease severity assessments

The disease infection of winter cereal varieties and breeding lines and the distribution of the pathogens was scored visually at the plot level on between 2-4 time points in the season, depending on the trial, and appearance of the pathogen. Disease severity was assessed using the different scales depending on the pathogen. Scores were recorded using percentage infection, Saari and Prescott (1975) 1–9 scale, or a modified Cobb scale (Stubbs et al., 1986). In the case of leaf spot diseases, some leaf samples with leaf spot symptoms were collected from experimental plots. The leaves were placed in a wet chamber and the pathogens found on the samples were determined after 1-3 days with stereo and light microscopes.

Wheat yield assessment

Analysis of the yield of 41 wheat varieties and lines bred in Martonvásár was examined in a replicated experiment under field conditions between 2022 and 2024, using conventional and a fungicide protected management systems (in 2023: 100 g L⁻¹ mefentriflukonazol and 100 g L⁻¹ piraklostrobin at stages 47-49 and 51-59 on the Zadoks scale (Zadoks et al., 1974) in 2024: 100 g L⁻¹ mefentriflukonazol and 100 g L⁻¹ piraklostrobin at stages 47-49 and 50 g L⁻¹ mefentriflukonazol, 100 g L⁻¹ protio-konazol at 51-59 on the Zadoks scale).

Wheat yield per cultivar was measured separately for each fungicide-treated and fungicide-untreated plot at 15% water content. Yield loss (%) was determined in each replication as the reduction in yield in fungicide-untreated plots compared to the yield in fungicide-treated plots.

$$\text{Yield loss (\%)} = ((Y_{tr} - Y_{un}) / Y_{tr}) * 100;$$

Y_{tr} = Grain yield in fungicide-treated plots;

Y_{un} = Grain yield in fungicide-untreated plots.

Statistical analysis

The data from field tests were analyzed using two- and multi-factor analysis of variance. For the two-factor analysis, the statistical module of

the Breeder program package developed at the Agricultural Research Institute of the Hungarian Academy of Sciences was used (Kuti et al., 2008). The multi-factor analysis of variance tests was performed using the MSTAT-C (Michigan State University, East Lansing, MI, USA) statistical program. Biplot Analysis module of Genstat 23rd ed. software (VSN International Ltd., Hemel Hempstead, UK). The strength of correlations was determined according to Evans (1996), who suggested five groups based on the absolute value of the correlation coefficient r : very weak (0.00-0.19), weak (0.20-0.39), moderate (0.40-0.59), strong (0.60-0.79) and very strong (0.80-1.00).

RESULTS AND DISCUSSION

Pathogen dominance conditions, yellow rust epidemic in 2023, leaf rust epidemic in 2024

We have assessed the occurrence of pathogens infecting winter cereals under field conditions in our breeding nurseries at several locations. The small plot experiments with wheat, durum wheat, and barley and oat varieties, were studied in 2023 at two sites, the deeper growing area with excellent soil conditions in Martonvásár (MV) and the shallower growing area with drier microclimate in Lászlópuszta (LP).

Occurrence of pathogens in 2023

Among the pathogens, powdery mildew infection appeared on all the cereal crops. The epidemic peaked in April, which coincided with the previous data suggesting ideal agro-meteorological conditions for infection (Wise, 1987; Liu et al., 2015) and then declined with the onset of warmer weather, except in the durum (Fig. 1.) trials in Lászlópuszta.

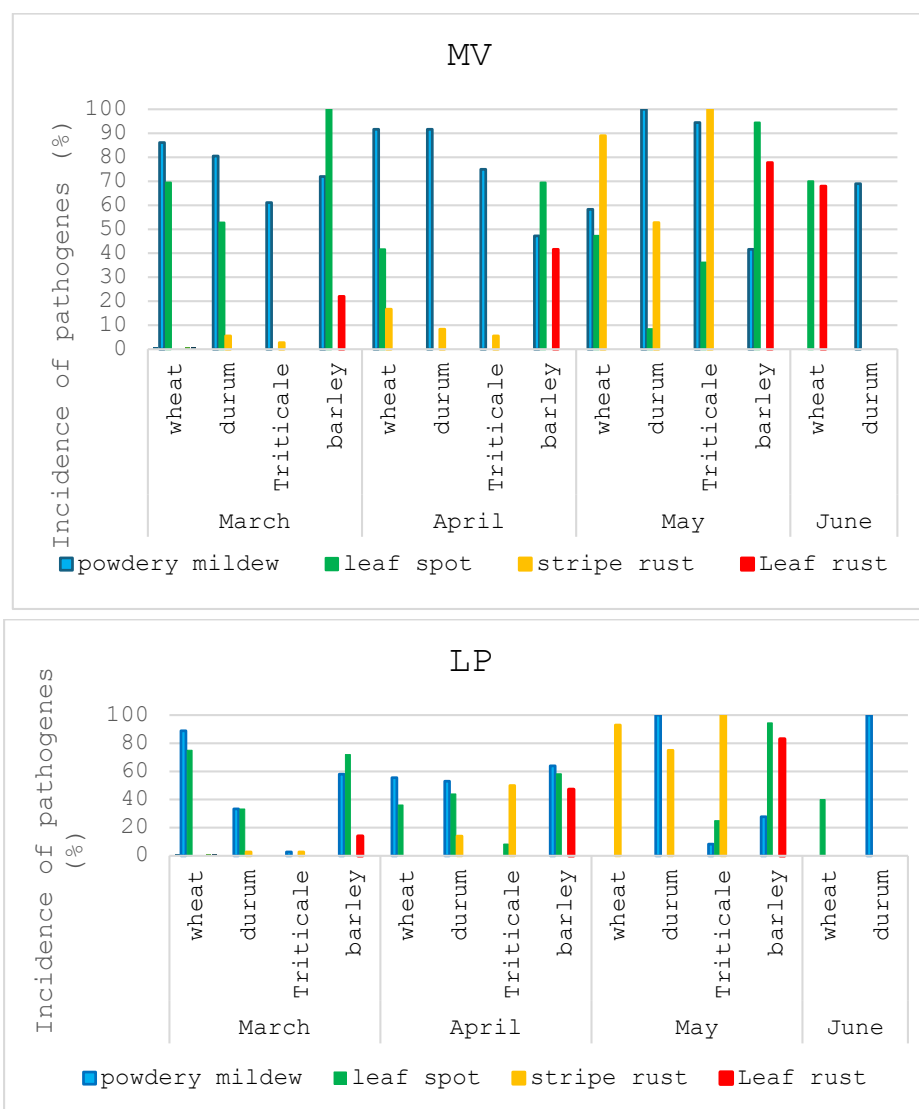
The year 2023 was largely defined by the early appearance of yellow rust, similar to the 2014 yellow rust outbreak (Csósz et al., 2014). This pathogen was first observed in early March, during a field evaluation in the artificial rust inoculation trails where varying degrees of initial stripe rust symptoms were detected in wheat, durum wheat and triticale.

Only traces of the pathogen were present during the first evaluation of the nurseries. Later, probably due to low temperatures (18 days below freezing temperature) (Table 1) and less rainfall until the end of April, the pathogen was present only in less than 20% of the experimental plots, except for the triticale trials at Lászlópuszta.

Traces of symptoms only appeared on the surface of the triticale leaves. In May, more precipitation arrived to the region, which, according to the results of several studies (Ali et al., 2017; Ali et al., 2022) has enhanced the development and

spread of the disease. In 89-93% of the plots, the characteristic conspicuous uredial rows were noticeable on the leaves in all triticale plots in both sites. Leaf rust appeared in early June, where yellow rust had left exposed leaf surface. The pathogen was present in 68% of the examined wheat experimental plots under MV management system.

In March, barley leaf rust (*Puccinia hordei*) was already present in 11-22% of the barley plots and by the end of the growing season, the pathogen was found in all plots at Lászlópuszta.



Notes: MV= Martonvásár nursery; LP = Lászlópuszta nursery

Figure 1. Incidence of cereal diseases in 2023 (Martonvásár)

Occurrence of pathogens in 2024

The presence of powdery mildew was observed in almost all plots. In May, this pathogen appeared only in trace amounts, even on susceptible varieties, only to the mid-leaf level of the plants, possibly due to higher spring temperatures and low rainfall, according to Tang et al. (2017). In June, powdery mildew was present in more than 80% of the tested trials at both locations.

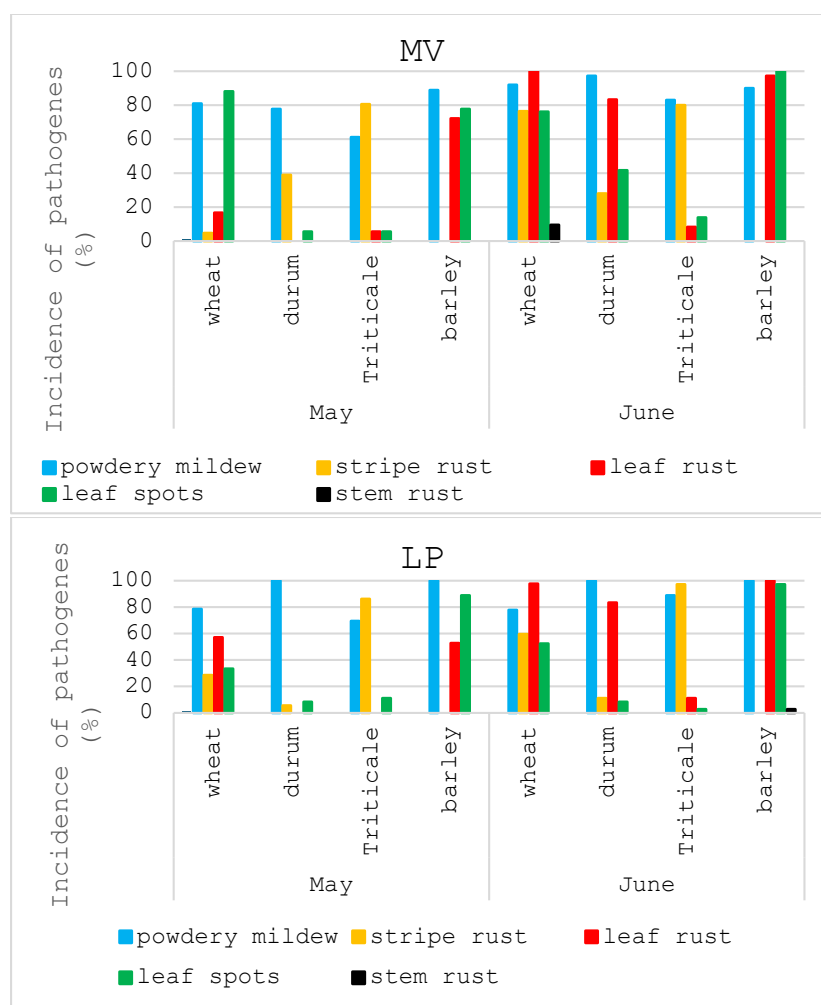
It was very likely that stripe rust infection would reappear based on the data obtained previous year and the forecasts in 2024. Nevertheless, only traces of leaf rust and *Septoria* leaf spot were noted in early February in the lower-lying Martonvásár (MV) nursery. El Jarroudi

et al. (2022) suggest that mild winters enhance *Septoria* infection. In April, yellow rust disease hotspots were found on some of the susceptible triticale varieties.

In May, stripe rust infected more than 80% of the triticale plots at both sites. As for the wheat trials, the pathogen was observed in the drier microclimate LP site, whereas in the durum wheat trials it was more frequently observed in the wetter microclimate MV (Figure 2) site.

As the leaves of the susceptible varieties were completely dried off by June, disease severity could have been assessed only by the presence of the spore-bearing pustules (teliospores).

Although leaf rust was already present in the Martonvásár nursery as early as February, the



MV= Martonvásár nursery; Notes: MV= Martonvásár nursery; LP = Lászlópuszta nursery

Figure 2. Incidence of cereal diseases 2024 (Martonvásár)

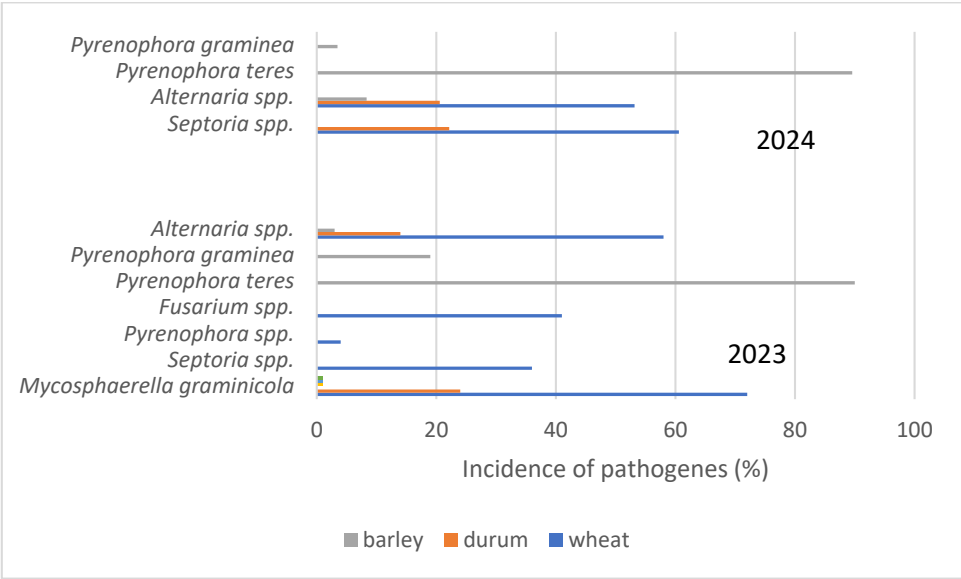
colder spring temperatures and limited precipitation – as highlighted by several studies (El-Orabey and Elkot, 2020; Naseri and Sasani, 2020; El Jarroudi et al., 2014) – may have affected the spread of the fungus. It still was not detected in the durum wheat trials in early May. Leaf rust was observed in 6% of the triticale plots, specifically at the lower-lying MV site. The pathogen appeared more frequently yet still sporadically in wheat trials sited in the Lászlópuszta (LP) field, which is characteristically drier and has shallower topsoil layer. By June, however, leaf rust was present in nearly all plots, with the exception of autumn-sown triticale.

In May, barley brown rust was observed on 53-72% of the plots and by June, it was present on nearly all plots at both sites. Toward the end of the growing season, symptoms of stem rust infection were noted on barley stems, coinciding with the observations reported by Orton et al. (2019). Microscopic analysis revealed elongated uredinia, characteristic of stem rust (Figure 6). Although, additional investigations are needed to confirm that the infection was caused by barley stem rust (*Puccinia graminis* f. sp. *tritici*).

In recent years depending on the conditions, stem rust infection with varying intensity has occurred in our nurseries.

In 2024, symptoms of stem rust were detected on 10% of the wheat genotypes in the Martonvásár site. Stem rust had disappeared from Hungarian wheat fields for decades, with no epidemics reported since 1972. However, in recent years, its resurgence has been reported across several regions of Europe, including the United Kingdom (Lewis et al., 2018), Germany (Olivera Firpo et al., 2017), southern Italy (Bhattacharya, 2017), Spain (Olivera et al., 2022), and Sweden (Berlin, 2017). Based on samples collected in Hungary between 2016 and 2019, the so-called “Sicilian” race – TTRTF or TTTTF (Bhattacharya, 2017), which caused significant economic damage in southern Italy – was identified both from Hungary (Tar et al., 2018) and the United States (Yue Jin, personal communication).

In both growing seasons, pathogen species responsible for leaf blotch symptoms were identified from symptomatic leaves. Microscopic analysis revealed that, in the majority of wheat samples, in addition to *Alternaria* spp., the pathogen of Septoria leaf blotch – *Zymoseptoria tritici* (formerly known as *Septoria tritici* or *Mycosphaerella graminicola*; (Quaedvlieg et al., 2011) – was present. In barley, *Pyrenophora teres* and *Pyrenophora graminea* were observed (Figure 3).



a. at the beginning of May 2023; b. at the end of May 2023

Figure 3. Results of microscopic study

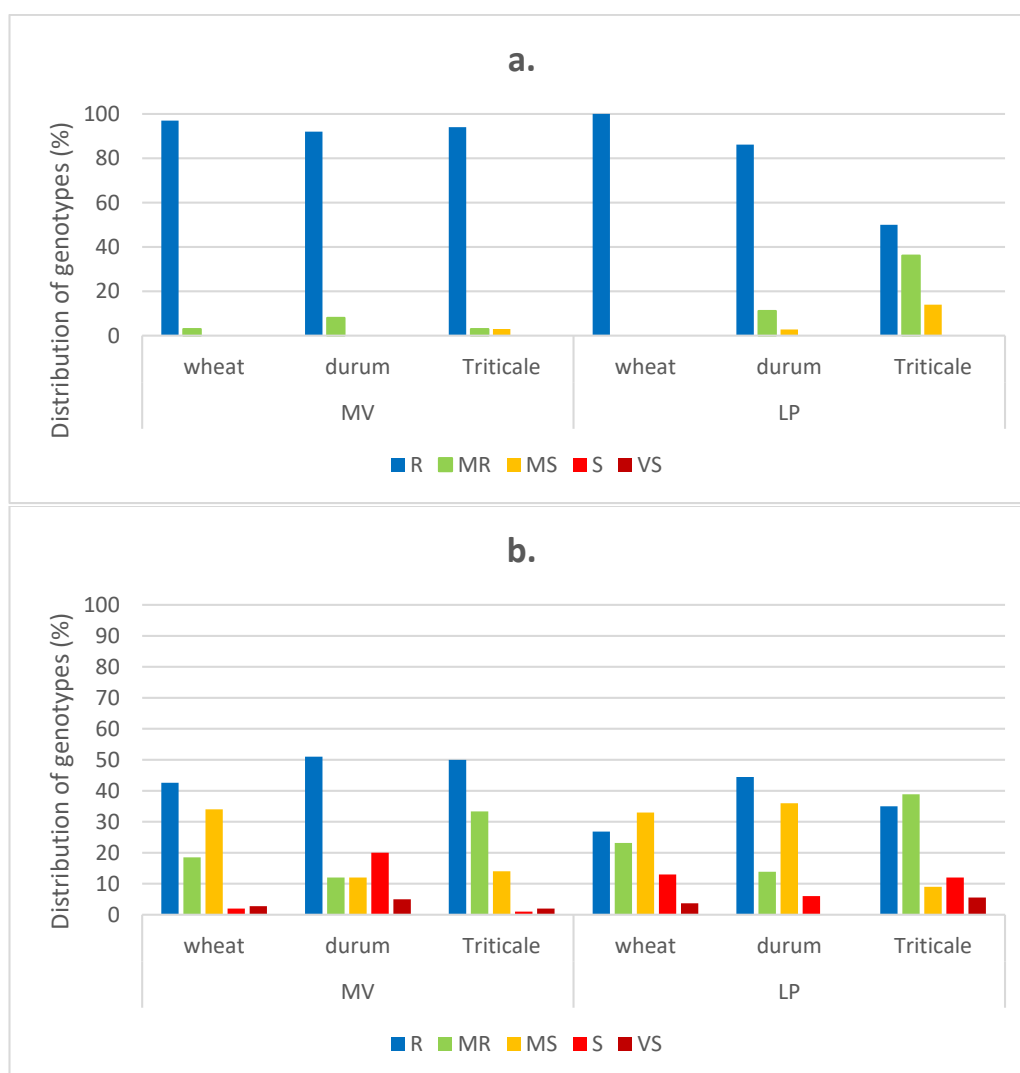
Resistance of cereal varieties and lines to rust infections

Resistance to leaf rust (Vida et al., 2009) and stem rust are tested and selected continuously in the artificially infected nurseries of the HUNREN CAR Agricultural Institute (Manninger, 1976). During the past eight years, such level of naturally occurring yellow rust and leaf rust infections has not been observed in our breeding nurseries. Therefore, the years 2023 and 2024 provided an exceptional opportunity for selecting resistant lines against both rust pathogens – based on previous publications - under during the epidemic, multiple pathotypes were assumed to

be present (Mesterházy et al., 2000; Goeyeau et al., 2006; Manninger, 2006; Kolmer et al., 2007; Hovmöller et al., 2016). In 2023 and 2024, the resistance of wheat varieties and lines bred in Martonvásár was assessed in two distinct microclimatic environments, along with monitoring the dynamics of pathogen spread.

Stripe or yellow rust

In April 2023, yellow rust occurred only sporadically in cereal crops. Even in early May, the proportion of moderately susceptible genotypes exceeded 10% only in the LP triticale trial (Figure 4a). However, following increased rainfall

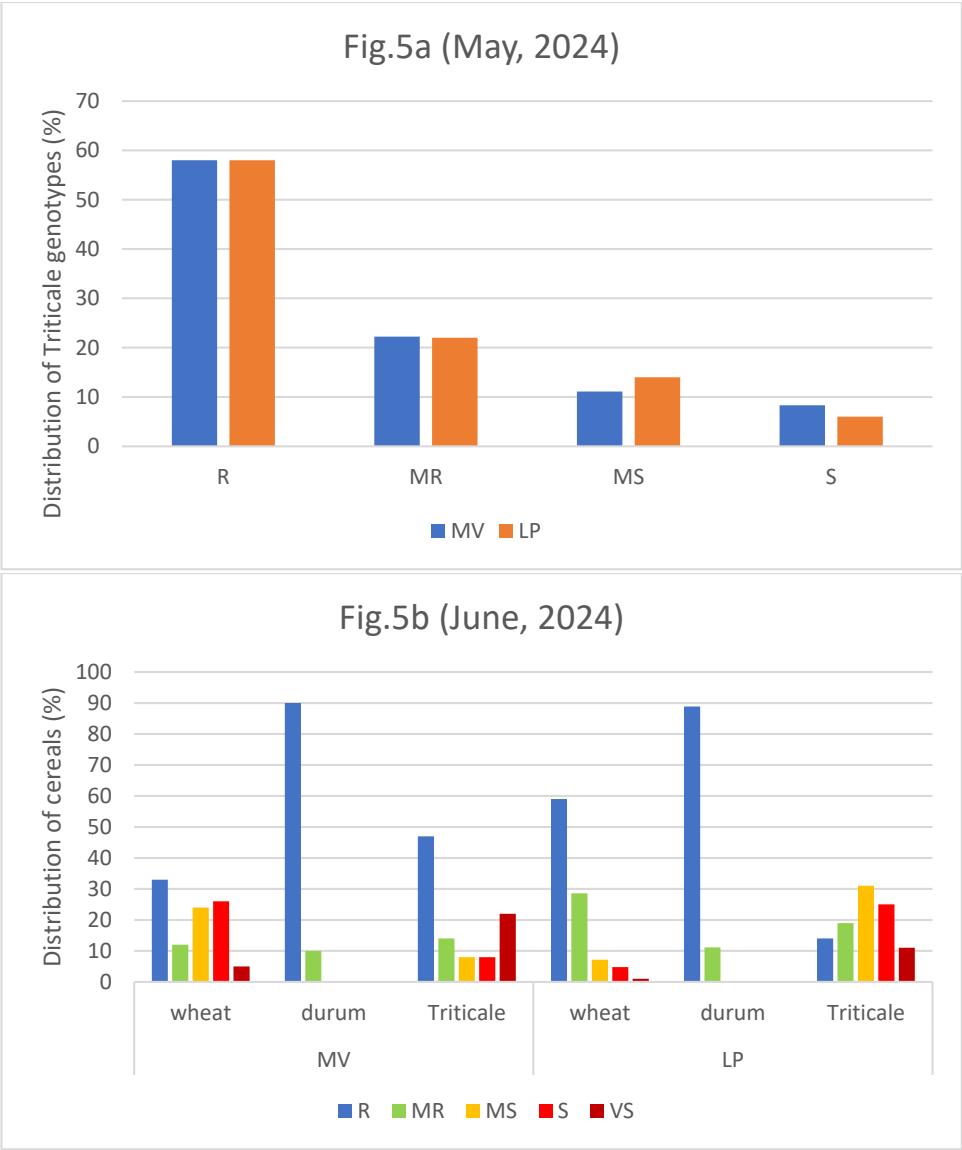


Notes: MV= Martonvásár nursery; LP = Lászlópuszta nursery; Yellow rust response; R= Resistant, MR: Moderately Resistant; MS: Moderately Susceptible; S: Susceptible

Figure 4. Percentage distribution of cereals on the basis of yellow rust resistance

during May, the infection escalated rapidly by the end of the month. This surge in disease incidence was accompanied by a rise in the frequency of genotypes categorized as moderately susceptible, susceptible, and highly susceptible, correlating with the increasing presence of the pathogen’s characteristic conspicuous elongated uredial rows. In certain cases – particularly within the triticale trials – yellow rust covered up to 60-100% of the flag leaf surface. According to the Global Rust Reference Center, multiple

races of the pathogen were present in Hungary in 2023, including Warrior, Triticale2015, Kalmár, and Amboise (www.wheatrust.org). Among these, the Warrior and Triticale2015 races (Hovmöller et al., 2016 and 2021) have caused severe epidemics in triticale and durum wheat across Europe. Nevertheless, approximately 50% of the tested cereal varieties and lines exhibited good resistance (Figure 4b). During field assessments, we observed that certain genotypes responded to infection with localized necrosis, effectively in-



Notes: MV= Martonvásár nursery; LP = Lászlópuszta nursery; Yellow rust response; R= Resistant, MR: Moderately Resistant; MS: Moderately Susceptible; S: Susceptible

Figure 5. Resistance of a. Triticale (in May, 2024)
b. cereal varieties and lines bred in Martonvásár to yellow rust in June (2024)

hibiting further pathogen development (Image 1). According to Župunski et al. (2024), the 2023 outbreak was more severe than the one in 2014. Other observations (Csősz et al., 2014) reported that, at some locations, the ratio of susceptible and resistant genotypes was equal. According to Vida et al. (2014b) many varieties bred in Martonvásár were resistant or moderately resistant.

As in the previous year, yellow rust was only sporadically observed in cereal crops in early May 2024. However, by the end of May, more severe infections were observed exclusively in the triticale trials. Despite this, more than half of the triticale varieties and lines exhibited resistance to the pathogen (Figure 5a). By June, the leaves of susceptible triticale varieties and lines had completely dried off, so the presence of the disease could only be deduced from the observation of yellow rust telia. At both locations, the proportion of susceptible wheat and triticale varieties and lines exceeded 20%. In contrast, durum wheat maintained excellent resistance even at this stage (Figure 5b).

Leaf or brown rust

In 2023, the resistance of wheat and durum wheat varieties and lines to leaf rust was assessed at the Martonvásár site. A total of 36% of the bread wheat genotypes and 75% of the durum wheat genotypes showed good resistance to the pathogen (Figure 6a). However, yellow rust infection and the early senescence of the affected leaves made evaluation difficult particularly in genotypes susceptible to yellow rust. This observation supports the findings of Jevtić and Župunski (2023), who reported that yellow rust was more aggressive in 2023, as reflected in both its higher incidence and the increased proportion of susceptible varieties. The authors also noted the co-occurrence of both rust pathogens, a phenomenon we also observed during our study, though we did not further analyze its impact on varietal susceptibility. In the following year, leaf rust appeared at both testing sites. By June, over 80% of the evaluated plots showed leaf rust symptoms. Despite the high pathogen pressure, durum wheat varieties and lines demonstrated excellent

resistance. Among the bread wheat genotypes, 28-52% showed tolerance to the leaf rust infection (Figure 6b).

Although barley dwarf rust was present in 70% of the plots in both breeding nurseries (MV and LP), more than half of the barley varieties and lines exhibited good level of resistance to the pathogen in both years. The high frequency of resistant genotypes is likely due to the fact that barley dwarf rust has been a frequent occurrence in Martonvásár in recent years, facilitating effective selection.

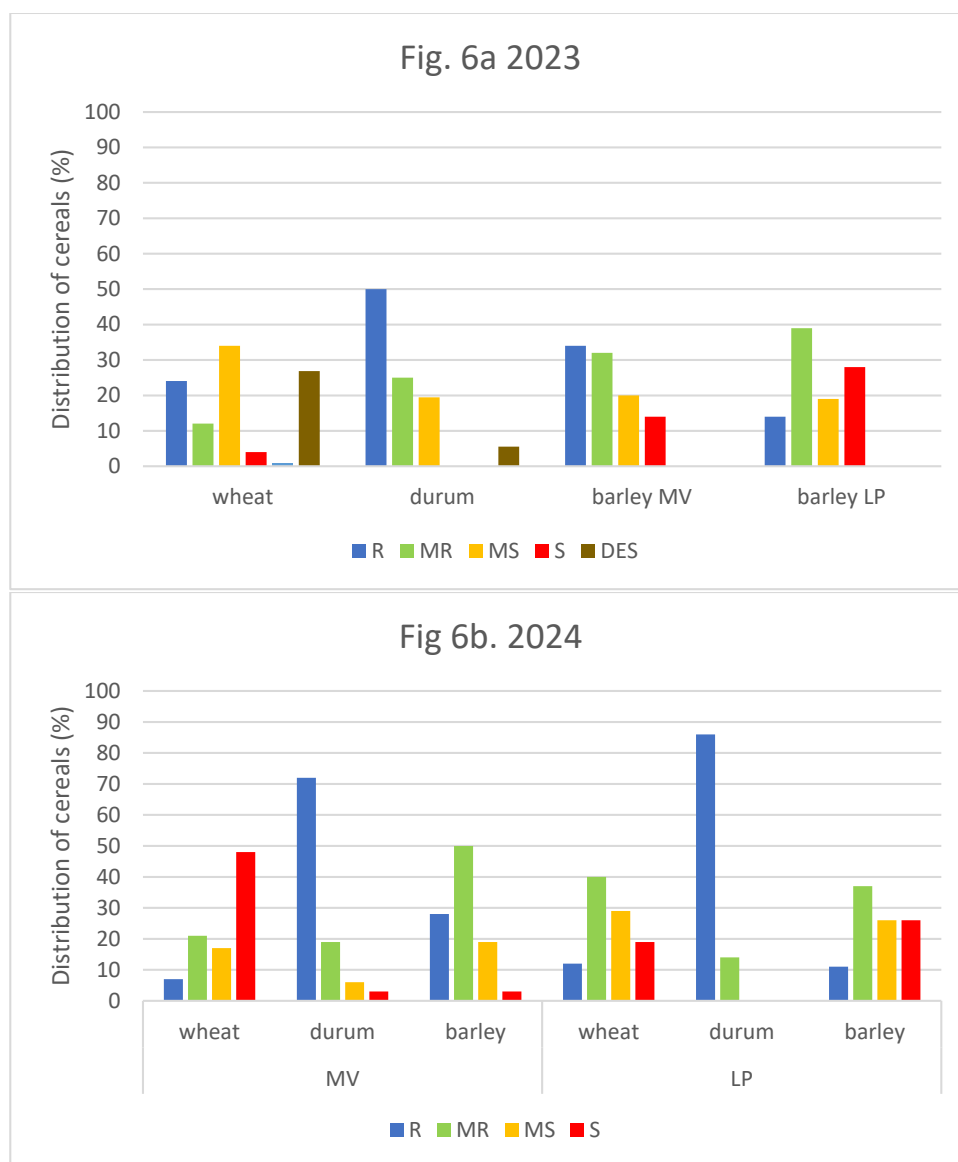
Effect of pathogens on yield in fungicide-treated and untreated winter wheat experiments

The analysis of variance (Table 2) revealed that both the year (Y) and the management system (M) had a highly significant effect on wheat yield across the studied genotypes ($p < 0.001$), indicating that environmental conditions and cultivation practices strongly influenced productivity. A significant Y×M interaction ($p < 0.05$) suggests that the effect of the management system slightly varied across years. The genotypic effect (G) was also highly significant ($p < 0.001$), confirm-

Table 2. Mean squares, significance levels of main, and interaction effects of yield and management system of wheat varieties and breeding lines bred in Martonvásár (Martonvásár, 2022-2024)

Source	Degrees of freedom	Mean Square
Y	1	135.812***
R	4	0.505
M	1	71.292***
Y×M	1	9.345*
G	40	6.039***
Y×G	40	1.536***
M×G	40	0.527**
Y×M×G	40	0.407 ^{ns}
Residual	320	0.299

Notes: Y, year; R, replication; M, management; G, genotype; *, **, *** the effect of the factor was significant at $p < 0.05$, < 0.01 , or < 0.001 level, respectively; ^{ns}=non significant



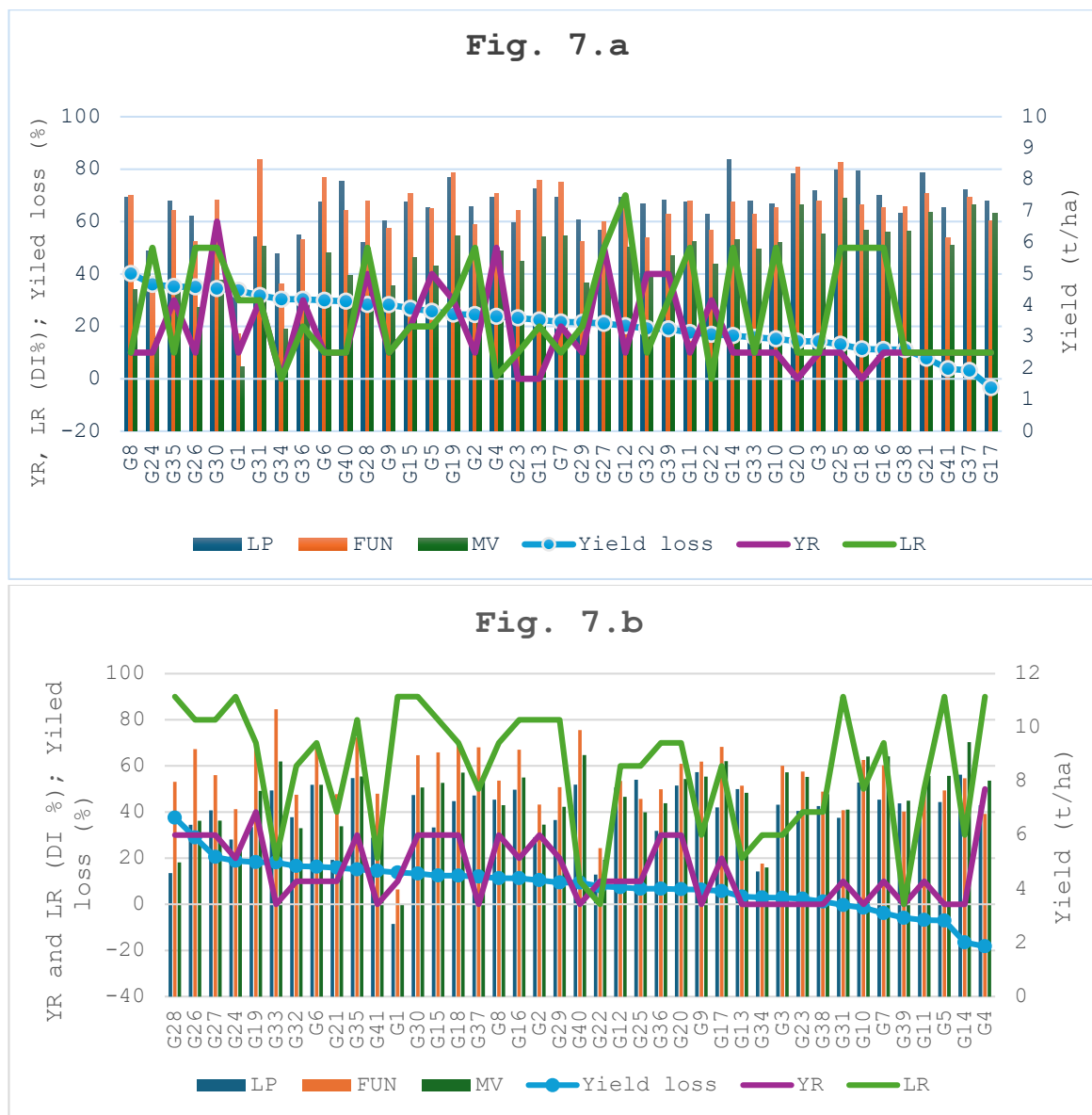
Notes: MV= Martonvásár nursery; LP = Lászlópuszta nursery; Leaf rust response; R= Resistant, MR: Moderately Resistant; MS: Moderately Susceptible; S: Susceptible

Figure 6. Resistance of cereal varieties and lines bred in Martonvásár to leaf rust in June a. 2023; b. 2024

ing the presence of substantial genetic variation in yield performance among the evaluated varieties and breeding lines (Gupta et al., 2022; Cséplő et al., 2025). Furthermore, significant $Y \times G$ ($p < 0.001$) and $M \times G$ ($p < 0.01$) interactions indicate that genotype responses were not consistent across years or management systems, underscoring the importance of multi-environment testing (Al-Askhar et al., 2023; Wang et al., 2025). However, the non-significant three-way interaction ($Y \times M \times G$) implies that no specific genotype

consistently outperformed others under a particular combination of year and management regime. The low residual variance further supports the reliability and precision of the experimental setup.

Yield and yield losses of 41 winter wheat varieties and breeding lines bred in Martonvásár were estimated in 2022/2023 and 2023/2024 growing seasons based under the untreated and fungicide treated conditions on grain yield ($t\ ha^{-1}$ and %) (Fig.7). In 2023, significantly lower mean yield was recorded ($6.2\ t\ ha^{-1}$) compared to



Notes: LP = Lászlópuszta nursery; FUN= fungicide treated nursery, MV= Martonvásár nursery; YR= yellow rust; LR= leaf rust

Figure 7. The yellow and leaf rust disease index, yield, and yield losses of 41 winter wheat varieties and breeding lines bred in Martonvásár were assessed in both 2022/2023 (Fig 7a) and 2023/2024 (Fig 7b) growing seasons

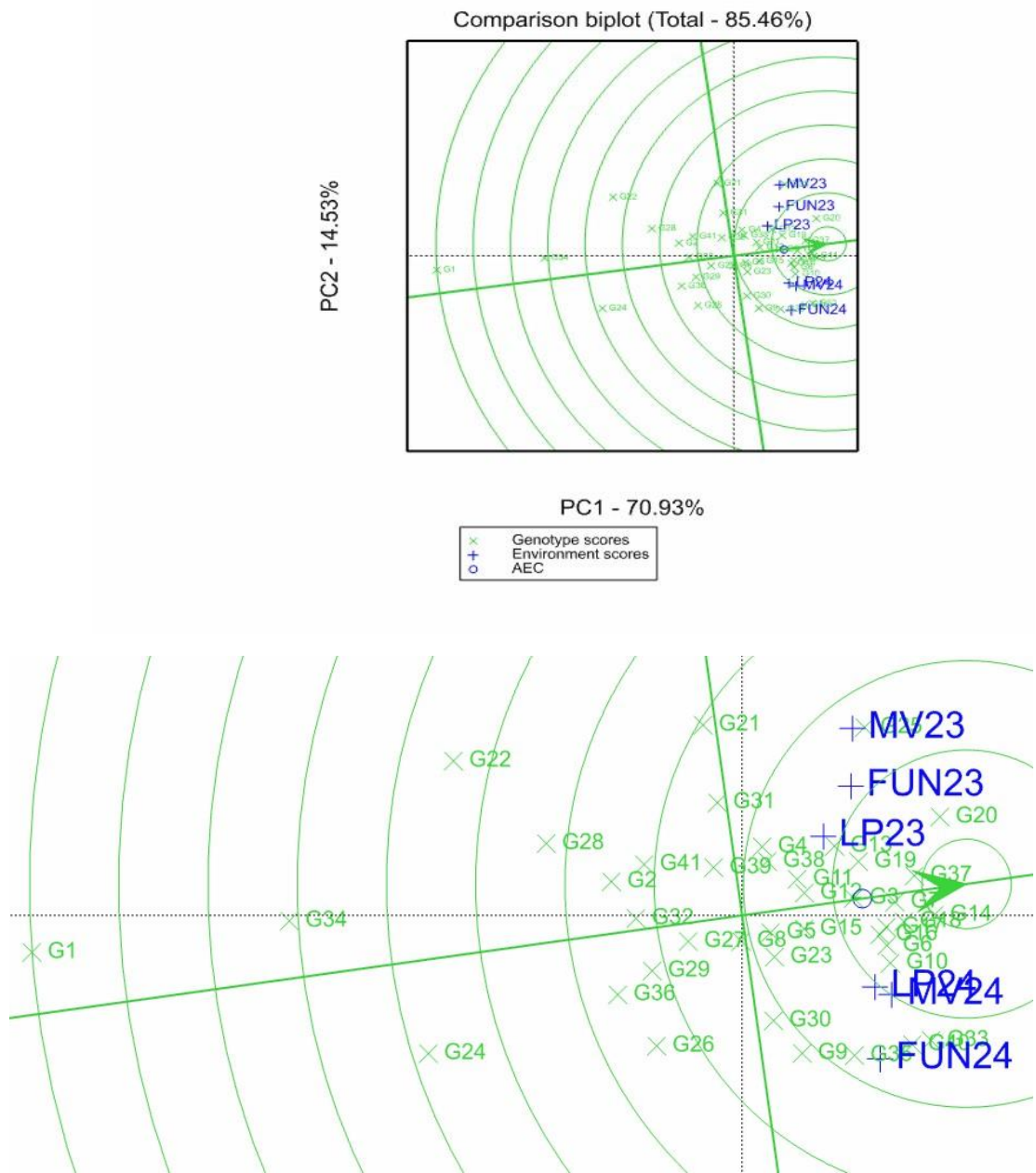
2024 (7.7 t ha⁻¹). In the fungicide-treated management system, yields ranged from 3.1 to 8.6 t ha⁻¹ in 2023, and from 4.0 to 10.7 t ha⁻¹ in 2024. In the untreated plots, yields ranged from 2.1 to 7.4 t ha⁻¹ in the first year, and from 3.4 to 9.5 t ha⁻¹ in the second year. Average yield loss in 2023 was 21.6%, while in the following year it decreased to 8.2%. The highest yield loss in 2023 was observed for genotype G8 (40.2%), while in 2024,

genotype G28 exhibited the highest loss (37.5%). According to our results, G8 showed moderate susceptibility in 2023, whereas G28 was susceptible to both rust pathogens in 2024. In the present study, several genotypes were identified that exhibited good resistance to both rust fungi and maintained stable yields. Several other research studies (Gál et al., 2002; Kiss and Veres, 2017; Župunski et al., 2024) observed different sensitiv-

ity among the genotypes. Our result confirmed that, the development of new resistant cultivars is the most economic and eco-friendly method to control plant diseases.

The correlation analysis revealed no significant relationship between yield loss and either yellow rust or leaf rust infection in the 2023 and 2024 seasons, aligning with the findings of Župunski

et al. (2024). However, when focusing on susceptible genotypes, a strong negative correlation ($r = -0.80^{***}$) was observed in untreated plots, consistent with the results reported by Voica et al. (2025). Additionally, a strong positive correlation ($r = 0.90^{***}$) was detected between yield loss and yellow rust severity in 2023. In contrast, no significant correlation was found between yield loss



Notes: LP23 = Lászlópuszta nursery in 2023; FUN23= fungicid treated nursery in 2023; MV23= Martonvásár nursery in 2023; LP24 = Lászlópuszta nursery in 2024; FUN24= fungicid treated nursery in 2024; MV24= Martonvásár nursery in 2024;

Figure 8. GGE comparison biplot based on yield of 41 winter wheat varieties and breeding lines bred in Martonvásár across six environments.

and leaf rust infection in any of the years examined.

The GGE biplot analysis, explaining 85.46% of the total variation (PC1: 70.93%, PC2: 14.53%), revealed considerable differences in yield performance and stability among the tested genotypes across six environments (MV23, FUN23, LP23, LR24, FUN24, and MV24). Among the tested genotypes, G3, G7 and G37 were positioned along the AEC (Average Environment Coordination) axis, in the direction of the ideal genotype, indicating high and stable performance across environments. These genotypes can be considered broadly adapted and are therefore recommended for general cultivation under diverse environmental conditions. Similar findings were reported by Akan and Akcura (2018), who used GGE biplot analysis to identify leaf rust resistant wheat genotypes with consistent performance across multiple locations in Turkey. Genotypes G13 and G19 were situated close to the environment vector representing LP23, indicating environment-specific adaptability. Their performance was high, but their stability was moderate. These genotypes may be suitable for specific environments, particularly where similar agro-climatic conditions to LP23 prevail. In our previous research (Cséplő et al., 2025) the GGE biplot proved useful in identifying genotypes with superior and stable performance, as well as in recognizing those with specific adaptation potential or instability. This insight supports more informed selection decisions in breeding programs aiming at both wide and specific adaptation. The use of GGE biplots has also been demonstrated in other studies for the selection of ideal genotypes resistant to abiotic (Bányai et al., 2020; Gupta et al., 2022) and biotic stresses (Akan and Akcura, 2018; Bosi et al., 2022).

CONCLUSIONS

In both years examined, weather conditions favored the spread of various rust diseases. In addition to the growing conditions, the variety's resistance is paramount for controlling pathogens

and achieving successful cereal production. In the upcoming decades, radical changes in arable crop production can be expected, as consumer society increasingly demands reliable and healthy food production. Resistance breeding and multi-pathogen resistant varieties can play a major role in this. Breeding programs in Martonvásár have long focused on producing high-yielding, high-quality and disease-resistant varieties.

As part of the 'Green Deal', the European Union has launched the 'Farm to Fork' strategy, which includes reducing the amount of pesticides used by 2030. To achieve this, the European Commission is prioritizing the promotion of integrated pest management procedures. It is obvious that these targets can only be achieved without destabilizing the situation of crop farms for example by using varieties that require fewer plant protection measures and are resistant to important diseases. Cultivating resistant varieties is the most cost-effective and environmentally friendly way to control plant diseases.

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Author contribution

All authors had role in study design, work, statistical analysis and manuscript writing.

Conflict of interest

There was not any conflict of interests.

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