RUDN Journal of Agronomy and Animal Industries. ISSN 2312-797X (Print). ISSN 2312-7988 (Online)
Вестник РУДН. Серия: АГРОНОМИЯ И ЖИВОТНОВОДСТВО
2025;20(3):354–367
http://agrojournal.rudn.ru

DOI: 10.22363/2312-797X-2025-20-3-354-367
EDN VAXWJL
UDC 631.527.21: 632.4.01.08: 632.938.1

Research article / Научная статья

Resistance of spring wheat *Triticum aestivum* L. to leaf rust under the conditions of the Central Non-Black-Earth region

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Abstract. The results of experimental studies on field resistance of spring common wheat (*Triticum aestivum* L.) varieties to leaf rust in the Central Region of the Non-Black Soil Zone of Russia were described. Fifteen spring wheat varieties were evaluated under field conditions from 2021 to 2024. The study aimed to analyze the yield performance of these varieties depending on the effectiveness of resistance genes (Lr genes) against leaf rust in the Central Non-Black Earth region of Russia. A search for relevant publications and identification of Lr genes in the varieties was conducted using databases such as Wheatpedigree, Scopus, NCBI, PubMed, Google Scholar, RSCI, and Cyberleninka. Resistance to brown rust was assessed using the 9-point VIR scale. The results showed that in years with favorable weather conditions from sprouting to heading, resistance to leaf rust positively influenced grain yield. However, during drought periods, this resistance had no significant effect on yield. Lr resistance genes in the studied varieties provided relatively effective protection in years with low infection pressure, but were insufficient during epidemic years. Therefore, more effective genes or their combinations should be considered when developing new varieties for the Central Non-Black Earth region of Russia. The most effective resistance genes identified from 2021 to 2024 were *Lr19* + *Lr6* (from the donor variety Tulaykovskaya 108) and *Lr21* (from the donor variety Granny).

Key words: *Puccinia triticina*, breeding for resistance, brown rust, Lr genes

Authors' contribution. Najodov B.B. — conducting field experiments, data collection, statistical analysis and interpretation of results, preparation of the original manuscript draft and approval of the final manuscript version; Rubets V.S., Divashuk M.G. — general scientific supervision, critical review, editing, and approval of the final manuscript version.

Conflict of interests. The authors declare no conflict of interests.

Article history: received 25 October 2024; accepted 10 July 2025.

For citation: Najodov BB, Rubets VS, Divashuk MG. Resistance of spring soft wheat *Triticum aestivum* L. varieties to leaf rust in conditions of Central Non-Black Earth region. *RUDN Journal of Agronomy and Animal Industries*. 2025;20(3):354–367. doi: 10.22363/2312-797X-2025-20-3-354-367 EDN: VAXWJL

Introduction

Reducing yield losses caused by fungal pathogens is an effective strategy to increase wheat production [1]. Pests and diseases worldwide account for 20–40% of crop yield losses and result in annual economic losses of about USD 220 billion[1]. Over time, due to prolonged natural selection and artificial breeding, wheat has lost many valuable disease resistance genes [3, 4]. *Puccinia triticina Eriksson (Pt)*, the pathogen responsible for wheat leaf rust, is one of the most destructive fungal pathogens affecting wheat. This disease is prevalent in most wheat-growing regions and causes significant yield losses in susceptible varieties under favorable climatic conditions [5–7]. The most effective, economically viable, and ecologically sustainable way to protect crops from diseases is through breeding and releasing resistant varieties. However, this issue remains unresolved in the Central Non-Black Earth and Black Earth zones of Russia [8].

According to some estimates, resistance to leaf rust conferred by a specific *Lr* gene lasts for no more than 5–7 years [9]. Therefore, the search for and utilization of new effective Lr genes is a pressing task for wheat breeding. The first widespread wheat variety resistant to leaf rust due to the *Lr14a* gene was Renown, registered in 1937 [10–12]. In the Central Region of Russia, resistance to leaf rust is provided by genes such as *Lr19, Lr23, Lr9, Lr24, Lr25, Lr28, Lr27, Lr31,* and *Lr39.*

In the Central Chernozem region, important genes include *Lr9, Lr44*, and *Lr49*, which confer juvenile resistance, while adult resistance genes such as *Lr24, Lr38, Lr39, Lr43, Lr49, LrTt1, LrTt2*, and *LrAgi* have shown high efficiency under field conditions [13, 14]. Literature analysis revealed that the *Lr10* gene, located on chromosome *1AS*, is present in varieties such as Zlata (st), Saratovskaya 74, Agata, Simbircit, and Margarita. This gene has been widely used in breeding programs in Russia, Australia, the USA, and at the CIMMYT international research center for many years [15].

To date, more than 82 *Lr* genes conferring resistance to leaf rust have been cataloged [16, 17], approximately 50% of which originate from other species. These genes are distributed across all 21 wheat chromosomes, with most located on the short arms [18, 19]. However, due to the size and complexity of the wheat genome, only ten genes — *Lr1, Lr9, Lr10, Lr13, Lr4a, Lr21, Lr22a, Lr34, Lr42*, and *Lr67* — have been cloned to date [6, 20–22].

The aim of this study was to assess the resistance of a selection of spring soft wheat varieties to leaf rust under natural infection conditions in the Central Non-Black Earth Zone, and to verify the presence of *Lr* genes previously reported in the literature.

[1] The Food and Agriculture Organization of the United Nations Home Page. Available from: https://www.fao.org/director-general/news/news arti-cle/zh/c/1301879/ [Accessed 15th November 2022].

Materials and Methods

The material for this study consisted of 15 spring common wheat varieties from the collection of the Russian State Agrarian University — Moscow Timiryazev Agricultural Academy (Table 1). Field experiments were conducted from 2021 to 2024, adhering to standard agricultural practices for the region. Resistance to leaf rust (brown rust) was evaluated using the universal 9-point scale established by the Vavilov Institute of Plant Industry (VIR). Leaf rust resistance was assessed using the universal 9-point scale developed by VIR. Evaluations were conducted twice: at the heading stage and at flowering, in accordance with methodological guidelines for the study of the global wheat collection[2]. A standard 9-point scale was applied: a score of 1 (very low resistance) corresponded to severe infection of the leaves (more than 50–100% of the area), a score of 3 (low resistance) indicated strong infection (~50%), a score of 5 (moderate resistance) reflected intermediate severity (20–30%), a score of 7 (high resistance) denoted mild symptoms (10–20%), and a score of 9 (very high resistance) represented no visible symptoms (0%).

Table 1

Material for the study

Variety	Breeding Center	Country	Year cultivar
Zlata (control)	Federal Research Center “Nemchinovka”, Verkhnevolzhsky Federal Agrarian Scientific Center)	Russia	2009
Saratovskaya 74	Federal Center of Agriculture Research of the South-East Region	Russia	2012
Agatha	Federal Research Center “Nemchinovka”	Russia	2014
Tulaykovskaya 108	Samara Federal Research Scientific Center RAS and FARC North-East	Russia	2014
Simbircit	Samara Federal Research Scientific Center RAS and FSUE “Kolos”	Russia	2006
Tymenskaya 29	Tyumen Scientific Centre SB RAS	Russia	2013
Obskaya 2	Institute of Cytology and Genetics SB RAS	Russia	2014
Tobolskaya	Federal Altai Scientific Center for Agrobiotechnology	Russia	2014
Altayskaya Zhnitsa	Federal Altai Scientific Center for Agrobiotechnology	Russia	2014
Margarita	Samara Federal Research Scientific Center RAS and JSC Privolzhskoye	Russia	2008
Uchitel	Federal Research Centre of Biological Systems and Agrotechnology’s of the RAS (Orenburg)	Russia	2001
Favorit	Federal Center of Agriculture Research of the South-East Region	Russia	2007
Granny	SAATBAU LINZ EGEN	Czech	2009
Triso	DEUTSCHE SAATVEREDELUNG AG (Lippstadt)	Germany	2004
Iren	FSBSI “Ural Federal Agrarian Scientific Research Centre”, Ural Branch RAS	Russia	1998

Source: compiled by B.B. Najodov.

[2] Dorofeev VF, Rudenko MI, Shitova IP, Korneichuk VA. ***Metodicheskie ukazaniya po izucheniyu mirovoi kollektsii pshenitsy*** [Guidelines for the study of the world wheat collection]. Leningrad: VIR; 1977. (In Russ.).

Cultivars with scores between 7 and 9 were classified as highly resistant[2]. Literature data (Table 2) were used to identify and verify Lr resistance genes in the examined cultivars[3].

Statistical analysis of experimental data included one-way analysis of variance (ANOVA) to determine the significance of varietal effects on yield under multi-year field trial conditions. In addition, principal component analysis (PCA) was applied to summarize and visualize the relationships among three key traits: grain yield, resistance to leaf rust, and the presence of resistance (Lr) genes. PCA revealed the differentiation of cultivars based on their adaptive responses across contrasting years, ranging from favorable to drought-affected seasons. This approach enabled a comprehensive evaluation of the contribution of both biotic and abiotic factors to yield formation. All calculations and visualizations were performed using the Python programming language (version 3.13) with the support of pandas, scipy, statsmodels, matplotlib, and sklearn libraries.

Results and Discussion

Brown rust does not occur annually in the conditions of the Central Non-Black Earth Zone, as its development depends on favorable meteorological conditions. Over the course of the research, the meteorological conditions varied significantly from year to year, leading to the absence of the disease in some years (Fig. 1, Table 2).

In 2021, sowing was delayed until May 11 due to excessive soil moisture and low temperatures. The first half of the growing season provided favorable conditions for plant development. However, the second half was marked by a severe drought combined with high air temperatures, which were unfavorable for the development of leaf rust. Despite these challenging conditions, a natural infection background for the disease was still present.

All wheat varieties were affected by leaf rust to varying degrees. The varieties Zlata, Tulaykovskaya 108, Altayskaya Zhnitsa, Margarita, Favorit, Granny, and Triso demonstrated a medium level of resistance, scoring 5 points on the 9-point VIR scale. Most of these varieties possess various Lr resistance genes, as identified in the literature (Table 2). Additionally, these varieties achieved high yields under these conditions (Fig. 2).

In contrast, the varieties Saratovskaya 74, Simbircit, Tymenskaya 29, Obskaya 2, and Tobolskaya exhibited higher resistance, scoring 7 points, and also demonstrated high yield performance. While literature sources did not confirm the presence of *Lr* resistance genes for all these varieties, their performance indicates their effectiveness in resisting the disease in the Central Non-Black Earth region environment.

The varieties Agata, Uchitel, and Iren showed varying degrees of susceptibility to brown rust. The results for the Agata variety, which carries the *Lr10* + *Lr19* gene com-

[3] Register of Breeding Achievements. Available from: https://gossortrf.ru/registry/ [Accessed 1st October 2024]. (In Russ.); GRIS — Genetic Resources Information System for Wheat and Triticale/ Available from: http://www.wheatpedigree.net/ [accessed 1 October 2024].

plex, were unexpected (Table 2). Despite a significant lesion, this variety demonstrated tolerance and produced a high yield (Fig. 2). Overall, the correlation analysis revealed a strong positive relationship between grain yield and resistance to brown rust in 2021, with a correlation coefficient of $r = 0.616$ (Fig. 3). The coefficient of determination (r^2) indicated that approximately 38% of the variability in wheat yield was determined by genotype.

In 2022, sowing occurred on May 5 under optimal conditions, which were typical for an average summer (Fig. 1). The period from sprouting to earing occurred at low temperatures with sufficient moisture, and the second half of the growing season experienced favorable moisture and increased air temperatures, negatively affecting yield (Fig. 2). During this period, there were no signs of brown rust, as a natural infection background was absent (Table 2). This likely contributed to the formation of the highest yields in some varieties over the four years of research, particularly in Margarita, Uchitel, Granny, Triso, and Iren (Fig. 2, Table 3), while the yields of other varieties remained at the 2021 levels.

Table 2

Resistance of spring wheat varieties to leaf rust, 2021–2024

Variety	Resistance, to leaf rust, score					Δ	Resistance genes, Reference
	2021	2022	2023	2024	Average		
Zlata (control)	5.0	9.0	9.0	3.0	6.5	b	*Lr10* [23]
Saratovskaya 74	7.0	9.0	9.0	3.0	7.0	ab	*Lr10* [24]
Agatha	3.0	9.0	5.0	3.0	5.0	c	*Lr10, Lr19* [25, 26]
Tulaykovskaya 108	5.0	9.0	7.0	7.0	7.0	a	*Lr19, Lr6* [27, 28]
Simbircit	7.0	9.0	9.0	3.0	7.0	ab	*Lr10* [29]
Tymenskaya 29	7.0	9.0	9.0	3.0	7.0	ab	–
Obskaya 2	7.0	9.0	9.0	3.0	7.0	ab	–
Tobolskaya	7.0	9.0	9.0	1.0	6.5	b	–
Altayskaya Zhnitsa	5.0	9.0	7.0	3.0	6.0	bc	–
Margarita	5.0	9.0	7.0	3.0	6.0	bc	*Lr49, Lr34, Lr10* [30]
Uchitel	3.0	9.0	9.0	3.0	6.0	bc	–
Favorit	5.0	9.0	7.0	1.0	5.5	c	*Lr6Agi* [31]
Granny	5.0	9.0	9.0	7.0	7.5	a	*Lr21* [32, 33]
Triso	5.0	9.0	7.0	3.0	6.0	bc	*Lr2a, Lr18, Lr20* [34–36]
Iren	1.0	9.0	5.0	5.0	5.0	c	–
Average	5.0	9.0	7.0	3.0	6.0		–

Note: Values with the same letters in the "Δ — Duncan's groups" column do not differ significantly at the $p \leq 0.05$ level. In 2022, there was no natural infection background for leaf rust.

Source: compiled by B.B. Najodov using MS Excel and MS Word.

In 2023, sowing was carried out at a favorable time — 22 April. The conditions of heat supply and moisture conditions favored rapid and friendly emergence of seedlings. However, further vegetation was accompanied by severe drought at moderate temperature (Fig. 1). As a result, wheat plants accelerated their development and, in general, insufficiently formed vegetative body. In the second half of the growing season, precipitation was distributed very unevenly. Under such conditions, leaf rust was weakly manifested (Table 2).

The varieties showed no visible signs of significant lesions in 2023. Only Tulaykovskaya 108, Altayskaya Zhnitsa, Margarita, Favorit, and Triso displayed a few pustules. Agata and Iren were the only varieties that exhibited an average level of resistance. Many varieties reduced their yields to the lowest level observed over the four-year period (Fig. 2), including Zlata (st), Tulaykovskaya 108, Simbircit, Tymenskaya 29, Obskaya 2, Altayskaya Zhnitsa, and Favorit. Yields for the other varieties were also lower compared to previous years. Given the minimal presence of rust in 2023, its effect on wheat yield was negligible, which is confirmed by the lack of correlation between yield and resistance in that year (Fig. 3, Table 3).

Analysis of grain yield data for spring wheat cultivars over 2021–2024 revealed significant variability both across years and among cultivars. The average yield ranged from 290.6 to 483.5 g/m². The lowest yields for most cultivars were recorded in 2023, likely due to unfavorable weather conditions during the early growing season. Cultivars such as Zlata (st), Tulaykovskaya 108, Obskaya 2, and Granny demonstrated relatively stable performance across years. The highest yield over the entire period (717 g/m²) was recorded for Margarita in 2022, although it showed considerable interannual variation (Δ = bc). One-way ANOVA showed significant differences among cultivars (LSD_{05} = 152.2 g/m²). Duncan's grouping of means identified the top-performing cultivars — Simbircit, Tobolskaya, Obskaya 2, and Tulaykovskaya 108, the latter belonging to group 'a', indicating high and stable productivity.

In 2024, after sowing on April 29, a sharp drop in temperature delayed sprouting, which occurred only on May 14. From sprouting to earing, the wheat experienced severe drought and high temperatures (Fig. 1), which, similar to 2023, prevented the plants from developing strong shoots. Later in the growing season, excessive precipitation and increased temperatures promoted the development of brown rust (Table 2). Among all the varieties, only Tulaykovskaya 108 and Granny exhibited high resistance (7 points), while Iren showed medium resistance (5 points), due to its earliness. The other varieties displayed varying degrees of susceptibility, ranging from 1 to 3 points. As a result, in 2024, a brown rust epidemic compounded by drought led to low grain yields (Fig. 2). Some varieties, such as Zlata, Tulaykovskaya 108, Simbircit, Tymenskaya 29, Altayskaya Zhnitsa, and Obskaya 2, were tolerant to the disease and produced slightly higher yields compared to 2023. However, the remaining varieties showed the lowest yields in the four-year study.

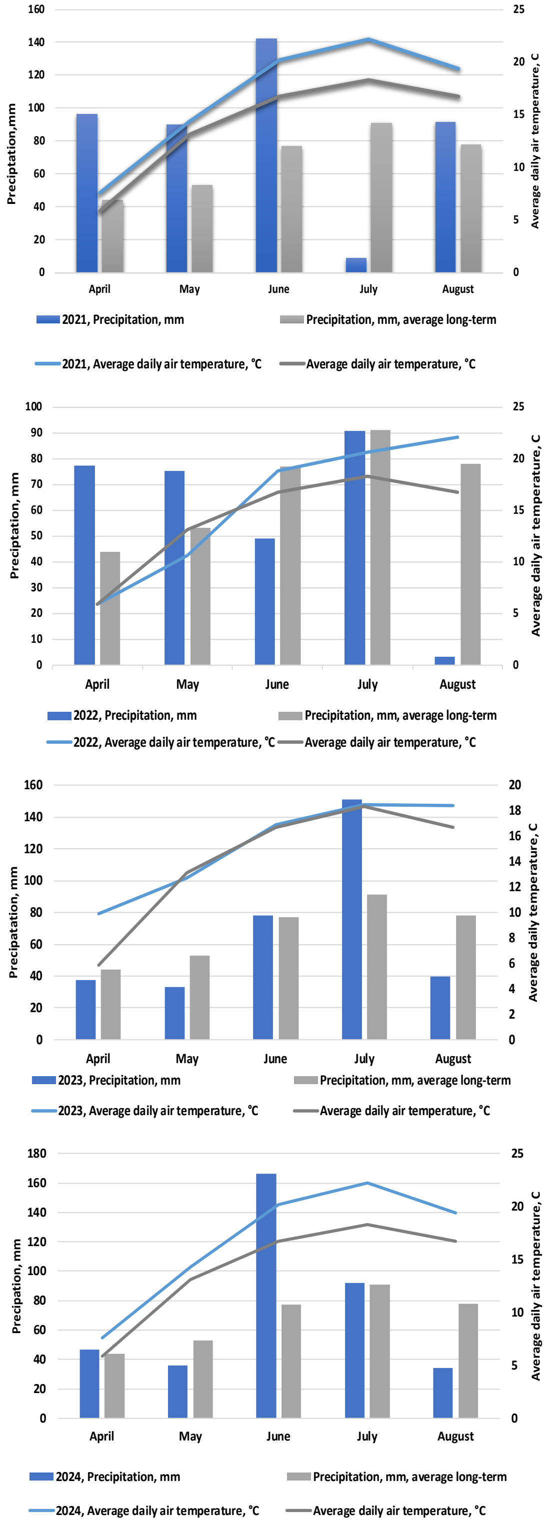

Fig. 1. Meteorological conditions during the study years (2021–2024)

Source: compiled by B.B. Najodov using MS Excel and MS Word.

Fig. 2. Yield of spring wheat varieties, g/m², by year and average (2021–2024) with LSD_{05} error bars and Duncan groupings

Source: compiled by B.B. Najodov with the use of Python 3.13.

Table 3

Grain yield of spring wheat cultivars, g/m², in 2021–2024

Variety	Yield, g/m²							Δ
	2021	2022	2023	2024	Average	min	max	
Zlata (st)	421.3	423	272.1	308.7	356.3	272.1	423.0	b
Saratovskaya 74	436.4	426.2	288.7	231.9	345.8	231.9	436.4	ab
Agata	456.8	415.6	270.7	189.5	333.2	189.5	456.8	c
Tulaykovskaya 108	426.9	294.4	252.1	356.5	332.5	252.1	426.9	a
Simbircit	478.5	483.5	269	313.6	386.2	269.0	483.5	ab
Tymenskaya 29	436.6	434.3	232.1	277.9	345.2	232.1	436.6	ab
Obskaya 2	499.6	469.3	258.9	397.5	406.3	258.9	499.6	ab
Tobolskaya	527.2	497.4	315.8	273.6	403.5	273.6	527.2	b
Altayskaya Zhnitsa	460.9	417.4	267.7	336.5	370.6	267.7	460.9	bc
Margarita	489.3	717	353.7	252.8	453.2	252.8	717.0	bc
Uchitel	311.9	466.4	219.4	164.6	290.6	164.6	466.4	bc
Favorit	511.3	498.8	201.4	205.3	354.2	201.4	511.3	c
Granny	467.9	500.7	282	198.7	362.3	198.7	500.7	a
Triso	397.4	431.4	276.8	227.5	333.3	227.5	431.4	bc
Iren	364	440.4	256.1	252.9	328.4	252.9	440.4	c
average	445.7	461.1	267.8	336.5	377.8	267.8	461.1	–
LSD_{05}	76.0	154.4	53.1	57.3	152.2	–	–	–

Note. Means followed by the same letter do not differ significantly at $p \leq 0.05$ (Duncan's multiple range test); LSD_{05} =g/m².

Source: compiled by B.B. Najodov using MS Excel and MS Word.

Principal component analysis (PCA), based on yield data, leaf rust resistance scores, and the presence of resistance genes, was used to differentiate spring wheat varieties according to their response to both biotic and abiotic factors under the conditions of the Central Non-Black Earth Region of Russia. The year-specific PCA plots (2021–2024) revealed that in more favorable conditions (e.g., 2022), varieties with high resistance formed distinct clusters associated with higher yields. In contrast, under abiotic stress such as drought (e.g., 2024), reduced vegetative growth was the primary limiting factor for yield, regardless of resistance level. These results indicate that varietal adaptability depends not only on disease resistance but also on the ability to cope with adverse environmental conditions, particularly moisture deficiency during early growth stages.

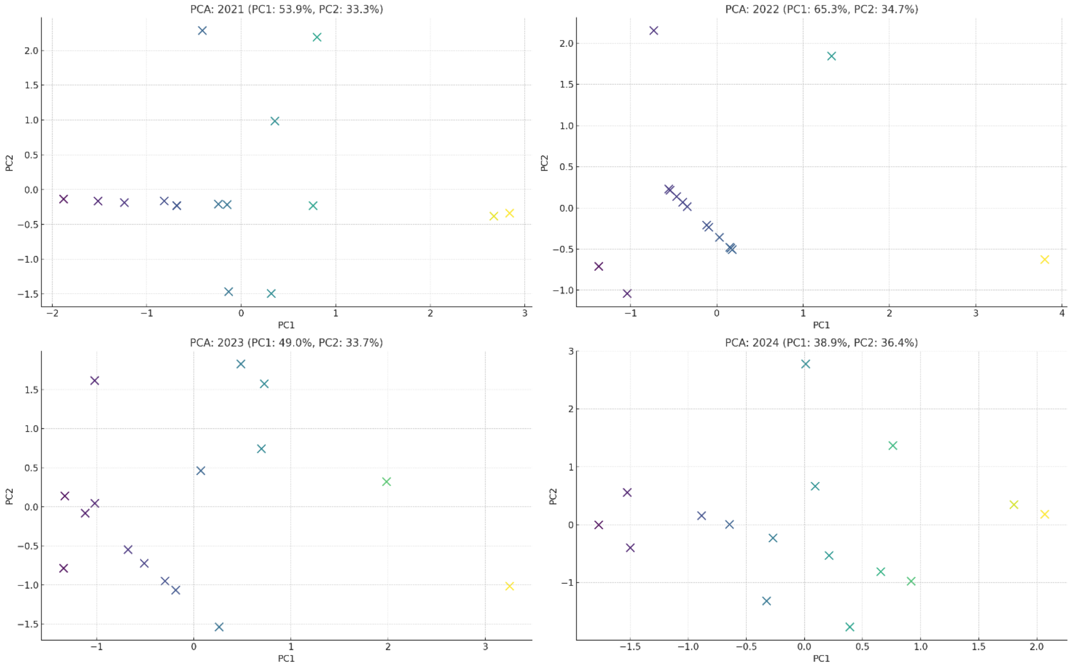

Fig. 3. Principal component analysis (PCA) of yield, resistance to leaf rust, and presence of resistance genes in spring wheat varieties (2021–2024)

Source: compiled by B.B. Najodov with the use of Python 3.13.

Regarding the resistance genes to brown rust in the studied common spring wheat varieties, it can be concluded that in years with a low natural infection background in the Central Non-Black Earth region of Russia, these genes effectively protect the plants from the disease. However, in years favorable for the development of epiphytotic, this protection becomes insufficient. According to our findings, the *Lr19* + *Lr6* gene combination (in the variety Tulaykovskaya 108) and the *Lr21* gene (in the variety Granny) provided the highest protection in the epiphytotic year.

Conclusion

In years with favorable meteorological conditions from sprouting to earing in the Central region of the non-Chernozem zone, the resistance of soft spring wheat varieties to brown rust positively influences grain yield. However, during droughts in this period, poor plant development becomes the main factor contributing to yield reduction. The *Lr* resistance genes present in the studied varieties provide relatively effective protection in years with low infection pressure. In epiphytotic years, however, their protection proves insufficient, highlighting the need for more effective genes or gene complexes in breeding new varieties for the Central Non-Black Earth region of Russia. The most effective genes identified during the 2021–2024 study were *Lr19* + *Lr6* (donor variety Tulaykovskaya 108) and *Lr21* (donor variety Granny).

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Устойчивость сортов яровой мягкой пшеницы *Triticum aestivum L.* к бурой ржавчине в условиях Центрального Нечерноземья

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Аннотация. Приведены результаты экспериментальных исследований полевой устойчивости сортов яровой мягкой пшеницы (*Triticum aestivum* L.) к бурой ржавчине в условиях Центрального района Нечерноземной зоны России (ЦРНЗ). Изучены 15 сортообразцов яровой мягкой пшеницы в полевых условиях в 2021–2024 гг. Цель исследования — установить зависимость урожайности сортов яровой пшеницы от эффективности генов устойчивости к бурой ржавчине в условиях ЦРНЗ. Для поиска публикаций по теме исследования и идентификации сортов с *Lr*-генами использованы базы данных Wheatpedigree, Scopus, NCBI, PubMed, Google Scholar, РИНЦ и Cyberleninka. Оценку устойчивости сортов к бурой ржавчине проводили по универсальной 9-балльной шкале ВИР. Выявлено, что в годы с благоприятными метеорологическими условиями в период от всходов до колошения устойчивость сортов пшеницы к листовой ржавчине положительно влияет на урожайность зерна, при засухе в этот период — нет. Гены устойчивости *Lr*, имеющиеся у изученного набора сортов, относительно эффективно защищают их в годы с невысокой инфекционной нагрузкой. В годы эпифитотий их защиты недостаточно. Поэтому следует искать более эффективные гены или их комплексы при создании новых сортов в ЦРНЗ. Наиболее эффективными за 2021–2024 гг. оказались гены *Lr19* + *Lr6* (донор сорт Тулайковская 108) и *Lr 21* (донор сорт Гранни).

Ключевые слова: *Puccinia triticina*, селекция на устойчивость, листовая ржавчина, Lr-гены

Вклад авторов: Наджодов Б.Б. — проведение полевых экспериментов, сбор и статистический анализ данных, интерпретация результатов, подготовка первоначального варианта рукописи, утверждение окончательной версии статьи; Рубец В.С., Дивашук М.Г. — общее научное руководство, критический анализ и редактирование текста рукописи, утверждение окончательной версии статьи.

Конфликт интересов. Авторы заявляют об отсутствии конфликта интересов.

История статьи: поступила в редакцию 25 октября 2024 г., принята к публикации 10 июля 2025 г.

Для цитирования: *Наджодов Б.Б., Рубец В.С., Дивашук М.Г.* Устойчивость сортов яровой мягкой пшеницы *Triticum aestivum* L. к бурой ржавчине в условиях Центрального Нечерноземья // Вестник Российского университета дружбы народов. Серия: Агрономия и животноводство. 2025. Т. 20. № 3. С. 354–367. doi: 10.22363/2312-797X-2025-20-3-354-367 EDN: VAXWJL