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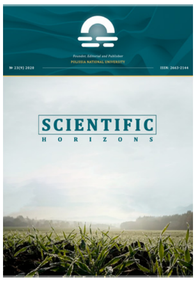

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Ecological plasticity of soft winter wheat varieties and resistance to snow mould pathogen (*Microdochium nivale* (Fr.) Samuels & I.C. Hallett)

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Abstract. Identifying superior genotypes of soft winter wheat with high ecological plasticity to soil and climatic conditions, combined with tolerance to common diseases caused by fungal pathogens, including snow mould, is becoming increasingly important for both production and breeding. This is driven by the global demand for

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environmentally safe products. The preliminary selection of the most valuable initial material with high-stress resistance to periodic climate changes and deteriorating phytosanitary conditions is essential for the success of the breeding process in addressing current challenges. This study aimed to determine the level of ecological plasticity in soft winter wheat varieties, differentiated by their resistance to the snow mould pathogen, through the analysis of genotype effect ranks and yield regression coefficients. Additionally, high-yielding sources were identified for use in breeding for adaptability. The research was conducted according to commonly accepted methodologies for evaluating materials based on disease resistance and adaptive traits, ensuring a highly objective interpretation of the results obtained. It was determined that the highest ecological plasticity among the studied material was differentiated by resistance to *Microdochium nivale* (Fr.) Samuels & I.C. Hallett, was exhibited by five varieties (16.7%) that achieved yields ranging from 118% to 129% of the standard. These include the varieties Muza Bilotserkivska, Askaniiska Berehynia, Hetmanska, Malovanka (UKR), and Nordika (CZE), as evidenced by the lowest sum of ranks (sum of ranks 2) for the genotypic effect (ε_i) and regression coefficient (R_i). New sources of high and stable resistance in soft winter wheat to the snow mould pathogen were identified, specifically: Sanzhara, Malovanka, Svitiaz, Muza Bilotserkivska (UKR); Smuga (POL), and Nordika (CZE). It was found that, in soft winter wheat varieties, resistance to *Microdochium nivale* (Fr.) Samuels & I.C. Hallett significantly negatively correlates with the sum of ranks for genotypic effect and yield plasticity, with $r = -0.69$, $P < 0.01$. The systematisation of the results obtained and the identification of varieties with the highest ecological plasticity under variable weather conditions within the agroecological zone allows for the identification of the best gene pool for adaptive breeding

Keywords: adaptability; homeostasis; epiphytotics; genotypic effect; variability; yield

INTRODUCTION

Periodic droughts, increasingly common in Ukraine due to global warming, along with the variability of prevalent pathogens affecting soft winter wheat, including snow mould (*Microdochium nivale* (Fr.) Samuels & I.C. Hallett) (syn. *Fusarium nivale* Ces. ex Berl. & Voglino), which is accompanied by the emergence of virulent and aggressive pathogens, highlight the priority of breeding for adaptability and the need to select valuable initial material based on these traits. Determining the ecological plasticity of soft winter wheat (*Triticum aestivum* L.) varieties and identifying sources of resistance to *M. nivale* (Fr.) Samuels & I.C. Hallett that exhibit high levels of adaptability to environmental stress are primary tasks in this endeavour. The successful resolution of these tasks supports the breeding process aimed at increasing total grain yield and stabilising production, which is of significant nutritional and economic importance. Soft winter wheat (*Triticum aestivum* L.) is a leading cereal crop in various countries, including Ukraine, due to its wide range of food products and high export potential. However, various biotic and abiotic environmental stress factors limit the genetic potential for yield and adaptability in this crop.

A Turkish scientist, F. Ünal (2024), in his research on the pathogenicity of *Microdochium* fungi in cereal crops, concluded that the level of infection by various snow mould pathogens in *T. aestivum* ranged from 83.29% to 91.52% and indicated a strong correlation with yield. Ukrainian researchers, O. Afanasyeva *et al.* (2023), emphasise the importance of cultivating disease-resistant plant varieties as a means of suppressing phytopathogens and preventing epidemics. Ukrainian scientists L. Murashko *et al.* (2022) note that among the various diseases of soft winter wheat in Ukraine, those caused by highly virulent fungi are becoming increasingly common. One such disease is snow mould, caused by the pathogen *Microdochium nivale* (Fr.) Samuels & I.C. Hallett (syn. *Fusarium nivale* Ces. ex Berl. & Voglino), which, due to its mutational, combinatorial, and population variability, is capable of overcoming the protective action of resistance genes in plants.

Researchers from China, S. Huang *et al.* (2020), assert that the snow mould pathogen, *M. nivale*, is a facultative parasite with distinctly expressed saprophytic properties. According to I. Furtat *et al.* (2020), this pathogen, when the infection is severe, leads to the death of the tillering node, roots, and the entire plant. K. Hockemeyer and P.L. Koch (2022) noted that snow mould manifests in the spring, immediately after the snow melts, with a white or pinkish coating appearing on the tillering node of infected plants. By studying the pathogenicity of 15 isolates of *M. nivale* through sequencing four genetic regions: elongation factor 1-alpha (*EF-1α*), β-tubulin, RNA polymerase II (*RPB2*), and internal transcribed spacer (ITS), Norwegian scientists – M. Abdelhalim *et al.* (2020) – concluded that the high heterogeneity of this pathogen is the reason for the widespread occurrence of snow mould in temperate climates, which, combined with provoking factors (snowfall on unfrozen soil, significant amount and duration of snow cover, presence of an ice crust, and increased doses of nitrogen fertilisers), significantly reduces plant immunity.

Several researchers, including A.V. Tyshchenko *et al.* (2023), note that the level of a genotype's resistance to environmental stressors characterises its stability. Plasticity is understood as the ability to adapt to a range of varying environmental conditions (Lenoir *et* *al.*, 2023). The ecological plasticity of a genotype, observed in its interaction with the environment, is one of the main factors that has the greatest influence on the variability and formation of yield. Ukrainian scientists M. Samoilyk *et al.* (2023) emphasise that for the successful introduction of new *T. aestivum* varieties into production, it is essential to assess both yield and adaptability.

Great attention is paid to optimal sowing dates as one of the elements of cultivation technologies necessary for the formation of high yields. Chinese researchers J. Liu *et al.* (2023) found that wheat yield and yield stability were highest when the photothermal potential was 16.0 t·ha^{-1} and the pre-winter active accumulated temperature regime was 400°C·d, which was observed when winter wheat was sown at the Gucheng station from 1 to 15 October during the 1997-2021 research period. M. Babar *et al.* (2022) note that the selection of wheat varieties with the necessary genetic variability of the traits under study contributes to the creation of stress-resistant genotypes as one of the important directions of modern breeding.

Therefore, the identification of soft winter wheat varieties with high ecological plasticity and resistance to *M. nivale* remains a relevant task. Successful resolution of this issue contributes to the creation of new genotypes with high adaptive capabilities. This study aimed to determine the ecological plasticity of soft winter wheat varieties by analysing the sum of genotypic effect ranks and the yield regression coefficient, and to identify sources with a high level of plasticity and resistance to *Microdochium nivale* (Fr.) Samuels & I.C. Hallett, which are well adapted to the limiting effects of prevalent stress factors.

MATERIALS AND METHODS

The research was conducted between 2020 and 2023 in an 8-field crop rotation at the Yuriev Plant Production Institute of the National Academy of Agrarian Sciences of Ukraine (NAAS), located in the eastern region of the Forest-Steppe zone. Standard agronomic practices for this ecological zone were applied. The study involved 30 soft winter wheat varieties developed in 12 countries, including 13 varieties of Ukrainian origin: Akademichna 100, Askaniiska Berehynia, Hetmanska, Kvitka Poliv, Liryka Bilotserkivska, Muza Bilotserkivska, Malovanka, Melashka, Merezhka, Musii, Sanzhara, Svitiaz, and Yuvileina Patona. The study also included three varieties from Austria – Aurelius, Dominikus, Turanus; three from the United States of America – Vanguard, Northern, Warhorse; two from Poland – Natula, Smuga; two from Azerbaijan – Gobustan, Ruzi 84; and one each from the Czech Republic – Nordika, the Netherlands – Manella, Romania – Armura, Germany – Rumor, Kazakhstan – Mida, Tajikistan – Sarvar, and Turkey – Yayla 302.

The experiments were conducted according to the methodology of qualification examination (Tkachyk, 2016). The accounting area of each plot was 5 m^2, with three replications. The standard variety used was Podolianka. The varieties were assessed following the methodology of S.O. Tkachyk (2016) and the methodology for evaluating the resistance of wheat varieties to pests and pathogens (Trybel *et al.*, 2010). The levels of resistance to *M. nivale* were rated using a nine-point scale, where 1 point indicated very low resistance (very severe damage, >70%), 3 points indicated low resistance (severe damage, 51-70%), 5 points indicated moderate resistance (average damage, 31-50%), 7 points indicated high resistance (slight damage, 10-30%), and 9 points indicated very high resistance (negligible damage, <10%).

The level of homeostasis (Hom) in soft winter wheat varieties regarding their resistance to *M. nivale* (Fr.) Samuels & I.C. Hallett was determined according to the methodology established by V.V. Khangildin and N.A. Lytvynenko (1981). This approach is based on the observed patterns of lower variability in the studied traits and a reduced decline in adverse conditions for samples exhibiting high homeostasis. The selection value (Sc) was also calculated using this methodology, which allows for the identification of genotypes that combine a high or moderate level of the trait in question with its stable expression under varying cultivation conditions (Khangildin & Lytvynenko, 1981).

The determination of ecological plasticity was conducted according to the methodology of B.P. Hurev *et al.* (1981). In this methodology, the genotypic effect (ε_i) indicates the level of overall adaptive capacity of the studied genotype, while the regression coefficient (R_i) reflects the degree of plasticity. Specifically, varieties with a high genotypic effect and a low regression coefficient occupy the highest rank (rank 1 – high), whereas the reverse scenario results in the lowest rank (rank 3 – low), and intermediate cases yield a medium rank (rank 2). Samples that achieve the lowest sum of ranks (between 2 and 3) during the study are considered the most valuable, as they combine a high potential with stability in the trait being investigated (Hurev *et al.*, 1981). For a qualitative assessment of the correlation coefficients, the R.E. Chaddock (1952) scale was employed. Statistical analysis of the experimental data was carried out using MS Excel 2007 and Statistica 6.0 software. The authors adhered to the standards outlined in the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS

The contrast in moisture availability across the different years of study, along with the prevalence of snow mould, enabled an assessment of the study material regarding ecological plasticity in yield and resistance to *M. nivale*. The hydrothermal coefficient (HTC) varied significantly by month and characterised the range of meteorological conditions, primarily from very dry to excessively moist. For example, the HTC for September varied from 0.05 to 2.14; October – from 0.16 to 3.53; April – from 0.61 to 2.55; May – from 0.57 to 1.29; June – from 0.22 to 1.25, and July – from 0.09 to 2.24. (Table 1).

***Table 1**. Hydrothermal coefficient during the growing seasons of the study, 2020-2023*

Year	Month					
	April	May	June	July	September	October
2020	-	-	-	-	0.05	0.87
2021	1.62	1.29	1.19	0.09	0.55	0.16
2022	0.61	0.57	1.25	1.09	2.14	3.53
2023	2.55	0.66	0.22	2.24	-	-
Mean annual HTC	1.2	0.88	1.04	1.1	1.0	1.67

***Source:** compiled by the authors*

To identify sources of resistance to *Microdochium nivale* (Fr.) Samuels & I.C. Hallett, the years 2021 and 2023 were favourable. The year 2022 was most favourable for achieving high yields. In other years of the study, the levels of its manifestation were generally lower. Over the period 2020-2023, the resistance of the studied soft winter wheat varieties to the snow mould pathogen varied from 1 to 9 points. As a result of the study, ten sources (33.3%) of soft winter wheat with a high level of resistance to *M. nivale* (Fr.) Samuels & I.C. Hallett (from 7 to 9 points) were identified: Sanzhara, Malovanka, Muza Bilotserkivska, Liryka Bilotserkivska, Melashka, Svitiaz (UKR); Smuga (POL); Nordika (CZE); Aurelius (AUT); Manella (NLD), and the standard variety Podolianka – 7 points (Table 2).

***Table 2**. Resistance of soft winter wheat varieties to the snow mould pathogen (Microdochium nivale (Fr.) Samuels & I.C. Hallett), 2020-2023*

Sample name	Country of origin	Resistance to snow mould pathogen, points			
		Range of variation		X_{med}	CV, %
		max	min		
Podolianka, standard	UKR	8.0	6.5	7.0	12.4
Sanzhara	UKR	9.0	8.0	8.5	5.9
Malovanka	UKR	9.0	8.0	8.3	6.9
Muza bilotserkivska	UKR	9.0	7.0	7.7	7.5
Liryka bilotserkivska	UKR	8.0	6.0	7.0	14.3
Melashka	UKR	8.0	6.5	7.0	12.4
Svitiaz	UKR	7.5	6.5	7.0	7.1
Akademichna 100	UKR	7.0	5.5	6.2	12.4
Kvitka poliv	UKR	7.0	5.5	6.2	12.4
Hetmanska	UKR	7.0	5.0	6.0	16.7
Askaniiska berehynia	UKR	6.0	4.0	5.2	20.2
Merezhka	UKR	6.0	4.0	5.2	20.2
Yuvileina Patona	UKR	6.0	4.0	5.0	20.0
Musii	UKR	5.0	3.0	4.3	26.7
Smuga	POL	9.0	7.0	7.7	7.5
Natula	POL	6.0	3.0	4.0	43.3
Nordika	CZE	9.0	7.5	8.2	9.4
Armura	ROU	4.0	3.0	3.3	17.3
Rumor	DEU	5.0	3.0	4.3	26.7
Aurelius	AUT	9.0	6.0	7.3	20.8
Turanus	AUT	6.0	3.0	4.0	43.3
Dominikus	AUT	3.5	1.0	2.2	58.1
Manella	NLD	9.0	5.0	7.0	28.6
Mida	KAZ	3.5	1.0	2.2	58.1

Table 2. Continued

Sample name	Country of origin	Resistance to snow mould pathogen, points			
		Range of variation		X_{med}	CV, %
		max	min		
Sarvar	TJK	4.0	1.0	2.3	65.5
Gobustan	AZE	4.0	2.0	2.7	43.3
Ruzi 84	AZE	4.0	1.0	2.3	65.5
Yayla 302	TUR	4.0	2.0	3.0	33.3
Vanguard	USA	6.0	4.0	5.0	20.0
Northern	USA	5.0	2.0	3.0	57.7
Warhorse	USA	4.0	2.0	3.0	33.3
$LSD_{0.05}$		–	–	0.8	–

Source: *compiled by the authors*

The following genotypes exhibited resistance to the snow mould pathogen at levels ranging from 4 to 6 points: Kvitka Poliv, Akademichna 100, Hetmanska, Merezhka, Askaniiska Berehynia, Yuvileina Patona, and Musii (UKR); Natula (POL); Turanus (AUT); Rumor (DEU); and Vanguard (USA), accounting for 36.7% of the varieties studied. Nine varieties (33.0%) demonstrated low levels of resistance to *M. nivale* (Fr.) Samuels & I.C. Hallett, namely: Armura (ROU); Dominikus (AUT); Mida (KAZ); Sarvar (TJK); Ruzi 84 and Gobustan (AZE); Yayla 302 (TUR); Northern and Warhorse (USA).

The coefficient of variation (CV, %) indicated that the variability of resistance to *M. nivale* (Fr.) Samuels & I.C. Hallett ranged from 5.9% to 65.5%. An analysis of the variation series revealed that six varieties – Sanzhara, Malovanka, Svitiaz, Muza Bilotserkivska (UKR), Smuga (POL), and Nordika (CZE) – exhibited low variability ($CV \leqslant 10.0\%$), comprising 20.0% of the samples. Eight samples, accounting for 26.7%, displayed medium variability (CV = 11.0% – 20.0%), including Melashka, Akademichna 100, Kvitka Poliv, Liryka Bilotserkivska, and Hetmanska (UKR); Armura (ROU); and Vanguard (USA). High variability (CV > 20.0%) in resistance to *M. nivale* was observed in the following varieties: Askaniiska Berehynia, Merezhka, Musii (UKR); Natula (POL); Aurelius, Turanus, and Dominikus (AUT); Rumor (DEU); Manella (NLD); Mida (KAZ); Sarvar (TJK); Gobustan and Ruzi 84 (AZE). It was determined that the proportion of samples exhibiting significant variability in resistance to the snow mould pathogen constituted 53.3%. The resistance of the standard variety, Podolianka, showed medium variability with a CV of 12.4%. The analysis indicated that the selection value (Sc) of the soft winter wheat varieties for resistance to *M. nivale* (Fr.) Samuels & I.C. Hallett varied from 0.6 to 7.6, while homeostasis (Hom) ranged from 3.6 to 144.5 (Fig. 1).

The study of selection value in soft winter wheat varieties for resistance to *M. nivale* (Fr.) Samuels & I.C. Hallett identified sources that exceeded the average value observed in the experiment (Sc = 3.7). These include 13 varieties (43.3%): Sanzhara (Sc = 7.6), Malovanka (Sc = 7.4), Muza Bilotserkivska (Sc = 6.2), Svitiaz (Sc = 6.1), Melashka (Sc = 5.7), Liryka Bilotserkivska (Sc = 5.3), Kvitka Poliv (Sc = 4.9), Akademichna 100 (Sc = 4.9), Hetmanska (Sc = 4.3) (UKR); Smuga (Sc = 6.2) (POL); Nordika (Sc = 6.8) (CZE); Aurelius (Sc = 4.9) (AUT); Manella (Sc = 3.9) (NLD); with the standard variety Podolianka (Sc = 5.7).

The criterion for homeostasis is the ability of genotypes to maintain a low level of variability for a trait over the study period. Among the material examined, genotypes exhibiting high homeostasis (Hom) and low variability ($CV \leqslant 10.0\%$) in resistance to *M. nivale* (Fr.) Samuels & I.C. Hallett were identified, specifically: Sanzhara (Hom = 144.5), Malovanka (Hom = 120.3), Svitiaz (Hom = 98.0), and Muza Bilotserkivska (Hom = 64.0) (UKR); Smuga (Hom = 64.0) (POL); and Nordika (Hom = 87.3) (CZE). Thus, the varieties Sanzhara (Sc = 7.6; Hom = 144.5), Malovanka (Sc = 7.4; Hom = 120.3), Svitiaz (Sc = 6.1; Hom = 98.0), Muza Bilotserkivska (Sc = 6.2; Hom = 64.0) (UKR); Smuga (Sc = 6.2; Hom = 64.0) (POL); and Nordika (Sc = 6.8; Hom = 87.3) (CZE) are valuable genotypes distinguished by their high selection value and homeostasis in resistance to *M. nivale* (Fr.) Samuels & I.C. Hallett.

To determine the ecological plasticity of winter soft wheat varieties differentiated by their resistance to *M. nivale* (Fr.) Samuels & I.C. Hallett, the research material was assessed based on the ranks of genotype effect and the regression coefficient of yield. Over the period from 2020 to 2023, sources were identified among the various eco-geographical origins of soft winter wheat that exhibited a high yield formation relative to the standard, specifically ranging from 118% to 129%. These include Svitiaz, Liryka Bilotserkivska, Yuvileina Patona, Muza Bilotserkivska, Askaniiska Berehynia, Hetmanska, and Malovanka (UKR); Nordika (CZE); and the standard Podolianka (UKR) with a yield of 5.73 t/ha (Table 3).

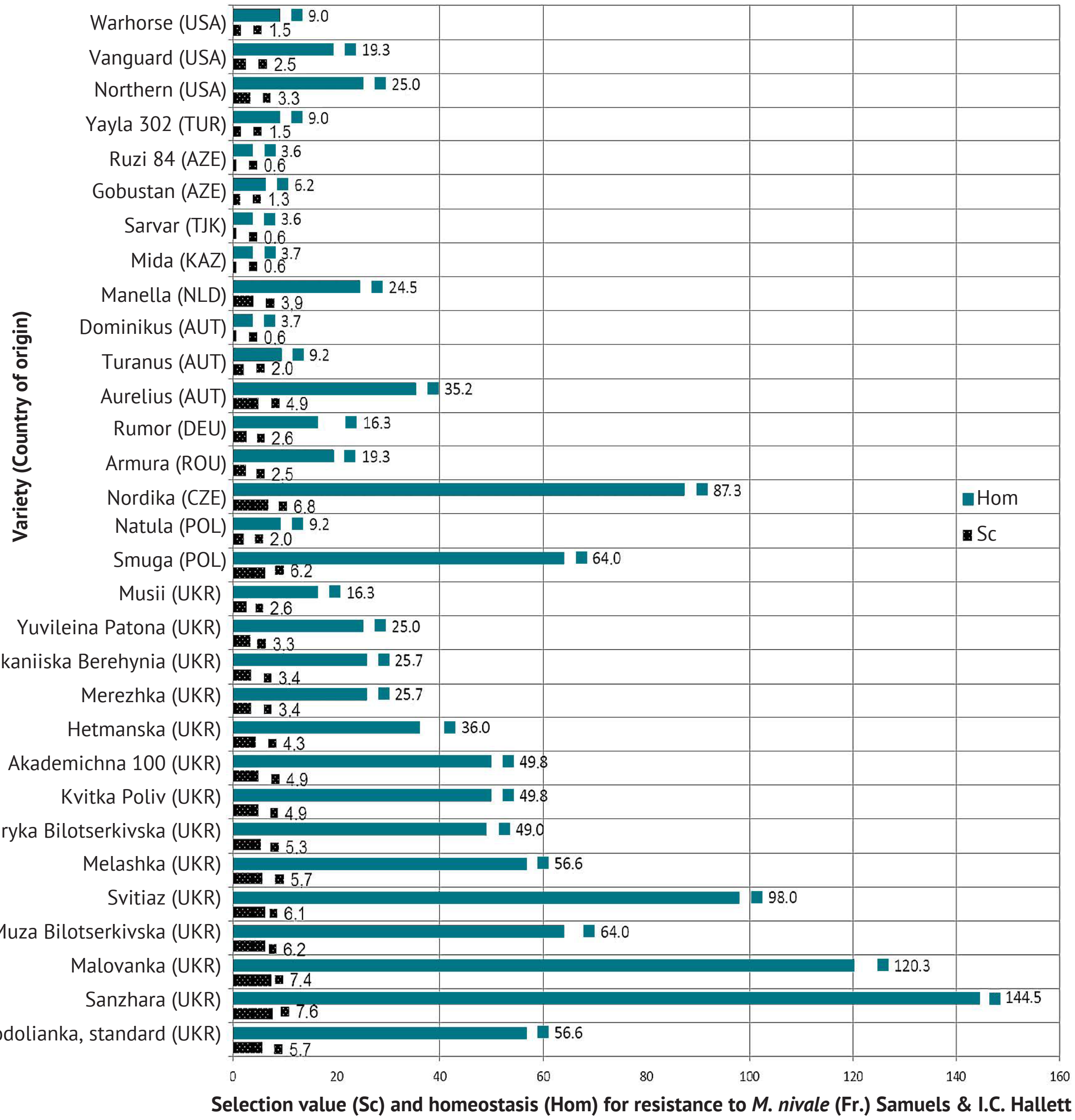

***Figure 2**. Parameters of selection value and homeostasis in soft winter wheat varieties for resistance to the snow mould pathogen (Microdochium nivale (Fr.) Samuels & I.C. Hallett), 2020-2023*

***Source:** compiled by the authors*

***Table 3**. Ecological plasticity of soft winter wheat varieties differentiated by resistance to Microdochium nivale (Fr.) Samuels & I.C. Hallett and yield, 2020-2023*

Variety name	Country of origin	Yield, t/ha			Genotype effect		Regression coefficient (degree of plasticity)		Ecological plasticity, the sum of ranks
		max	min	med	ε_i	rank	R_i	rank	
Podolianka, standard	UKR	7.15	4.78	5.73	-0.30	2	0.94	2	4
Svitiaz	UKR	8.35	6.12	7.42	1.39	1	0.88	2	3
Liryka Bilotserkivska	UKR	9.04	5.74	7.37	1.34	1	1.31	3	4
Yuvileina Patona	UKR	9.22	5.35	7.29	1.26	1	1.54	3	4
Muza Bilotserkivska	UKR	7.82	6.45	7.17	1.14	1	0.54	1	2
Askaniiska berehynia	UKR	7.65	6.25	6.86	0.83	1	0.56	1	2
Hetmanska	UKR	7.50	6.30	6.84	0.81	1	0.31	1	2
Malovanka	UKR	7.95	5.93	6.74	0.71	1	0.80	1	2
Melashka	UKR	7.80	5.54	6.62	0.59	1	0.90	2	3
Kvitka Poliv	UKR	7.85	5.64	6.62	0.59	1	0.88	2	3

Table 3. Continued

Variety name	Country of origin	Yield, t/ha			Genotype effect		Regression coefficient (degree of plasticity)		Ecological plasticity, the sum of ranks
		max	min	med	ε_i	rank	R_i	rank	
Musii	UKR	7.10	5.78	6.48	0.45	1	0.52	1	2
Merezhka	UKR	7.90	5.08	6.41	0.38	1	1.12	2	3
Akademichna 100	UKR	7.57	5.34	6.32	0.29	2	0.89	2	4
Sanzhara	UKR	7.40	5.5	6.22	0.19	2	0.76	1	3
Natula	POL	6.80	6.25	6.52	0.49	1	0.22	1	2
Smuga	POL	6.74	5.33	5.97	-0.06	2	0.56	1	3
Nordika	CZE	7.50	6.26	7.02	0.99	1	0.49	1	2
Armura	ROU	7.86	4.42	6.01	-0.02	2	1.37	3	5
Rumor	DEU	7.42	4.26	5.83	-0.20	2	1.26	3	5
Turanus	AUT	7.95	4.33	6.08	0.05	2	1.44	3	5
Aurelius	AUT	6.90	4.85	5.93	-0.10	2	0.81	1	3
Dominikus	AUT	7.76	3.27	5.90	-0.13	2	1.78	3	5
Manella	NLD	7.36	4.10	5.97	-0.06	2	1.29	3	5
Mida	KAZ	6.30	2.60	4.48	-1.55	3	1.47	3	6
Sarvar	TJK	7.26	3.50	5.39	-0.64	3	1.49	3	6
Ruzi 84	AZE	5.71	3.21	4.62	-1.41	3	0.99	2	5
Gobustan	AZE	5.65	2.95	4.57	-1.46	3	1.07	2	5
Yayla 302	TUR	6.44	2.75	4.55	-1.48	3	1.47	3	6
Vanguard	USA	7.25	3.42	5.31	-0.72	3	1.52	3	6
Warhorse	USA	5.62	3.15	4.37	-1.66	3	0.98	2	5
Northern	USA	5.30	3.25	4.35	-1.68	3	0.81	1	4
LSD $_{0.05}$		–	–	0.35	–	–	–	–	–
min		5.30	2.60	4.35	-1.68	1	0.22	1	2
max		9.22	6.45	7.42	1.39	3	1.78	3	6
med		7.29	4.76	6.03	0.00	–	1.00	–	–

Source: *compiled by the authors*

Thirteen varieties, constituting 43.3%, were distinguished by high values of genotype effect (rank 1) for yield. These included the following samples: Svitiaz, Liryka Bilotserkivska, Yuvileina Patona, Muza Bilotserkivska, Askaniiska Berehynia, Hetmanska, Malovanka, Melashka, Kvitka Poliv, Musii, and Merezhka (UKR); Natula (POL); and Nordika (CZE). The varieties Akademichna 100 and Sanzhara (UKR); Smuga (POL); Armura (ROU); Rumor (DEU); Turanus, Aurelius, and Dominikus (AUT); and Manella (NLD) exhibited an average genotype effect (rank 2), representing 30.0% of the samples. A low level of genotype effect (rank 3) was characteristic of eight varieties (26.7%), namely Mida (KAZ); Sarvar (TJK); Ruzi 84, Gobustan (AZE); Yayla 302 (TUR); and Vanguard, Warhorse, and Northern (USA). The standard Podolianka (UKR) demonstrated an average level of genotype effect for yield (rank 2). The conducted research established that the genotype effect (ε_i) for yield among the differentiated varieties resistant to *M. nivale* ranged from 1.68 to 1.39.

Based on the degree of plasticity (R_i), it was determined that the number of homeostatic samples exhibiting high stability in yield performance (rank 1) included 11 varieties, accounting for 36.7%. The following varieties were characterised by this genotype capability: Muza Bilotserkivska, Askaniiska Berehynia, Hetmanska, Malovanka, Musii, and Sanzhara (UKR); Natula and Smuga (POL); Nordika (CZE); Aurelius (AUT); and Northern (USA). Eight varieties (26.7%), including Svitiaz, Melashka, Kvitka Poliv, Merezhka, and Akademichna 100 (UKR); Ruzi 84 and Gobustan (AZE); and Warhorse (USA), were classified as moderately sensitive genotypes for yield in variable growing conditions (rank 2). The number of intensive, or sensitive, genotypes that respond to both improved and worsened growing conditions (rank 3) totalled 11 varieties, also constituting 36.7%. These included Liryka Bilotserkivska, Yuvileina Patona (UKR); Armura (ROU); Rumor (DEU); Turanus and Dominikus (AUT); Manella (NLD); Mida (KAZ); Sarvar (TJK); Yayla 302 (TUR); and Vanguard (USA). The standard Podolianka was characterised by average sensitivity to variable growing conditions (rank 2).

In investigating the ecological plasticity of soft winter wheat varieties differentiated by their resistance to the snow mould pathogen, based on an analysis of the sum of the ranks of the genotype effect (ε_i) and the regression coefficient (R_i) for yield, seven varieties (23.3%) were identified as having the highest genetic potential for adaptability, and consequently the greatest breeding value, as indicated by the lowest sum of ranks (sum of ranks 2). These varieties are: Muza Bilotserkivska ($\varepsilon_i = 1.14$; $R_i = 0.54$), Askaniiska Berehynia ($\varepsilon_i = 0.83$; Ri = 0.56), Hetmanska ($\varepsilon_i = 0.81$; $R_i = 0.31$), Malovanka ($\varepsilon_i = 0.71$; $R_i = 0.80$), Musii ($\varepsilon_i = 0.45$; $R_i = 0.52$) (UKR); Natula ($\varepsilon_i = 0.49$; $R_i = 0.22$) (POL); and Nordika ($\varepsilon_i = 0.99$; $R_i = 0.49$) (CZE). The samples Sanzhara ($\varepsilon_i = 0.19$; $R_i = 0.76$), Svitiaz ($\varepsilon_i = 1.39$; $R_i = 0.88$), Melashka ($\varepsilon_i = 0.59$; $R_i = 0.90$), Kvitka Poliv ($\varepsilon_i = 0.59$; $R_i = 0.88$), and Merezhka ($\varepsilon_i = 0.38$; $R_i = 1.12$) (UKR); Smuga ($\varepsilon_i = 0.06$; $R_i = 0.56$) (POL); and Aurelius ($\varepsilon_i = 0.10$; $R_i = 0.81$) (AUT) were somewhat less notable in terms of total rank (sum of ranks 3). 13.3 % of varieties achieved a total rank of 4: Akademichna 100 ($\varepsilon_i = 0.29$; $R_i = 0.89$), Liryka Bilotserkivska ($\varepsilon_i = 1.34$; $R_i = 1.31$), Yuvileina Patona ($\varepsilon_i = 1.26$; $R_i = 1.54$) (UKR); and Northern ($\varepsilon_i = 1.68$; $R_i = 0.81$) (USA). A total rank of 5 was assigned to varieties of foreign breeding, specifically: Armura ($\varepsilon_i = 0.02$; $R_i = 1.37$) (ROU); Rumor ($\varepsilon_i = 0.20$; $R_i = 1.26$) (DEU); Turanus ($\varepsilon_i = 0.05$; $R_i = 1.44$), Dominikus ($\varepsilon_i = 0.13$; $R_i = 1.78$) (AUT); Manella ($\varepsilon_i = 0.06$; $R_i = 1.29$) (NLD); Ruzi 84 ($\varepsilon_i = 1.41$; $R_i = 0.99$), Gobustan ($\varepsilon_i = 1.46$; $R_i = 1.07$) (AZE); and Warhorse ($\varepsilon_i = 1.66$; $R_i = 0.98$) (USA), which constitute 26.7%. The four varieties with the lowest adaptability potential, as assessed by genotype effect and degree of plasticity (sum of ranks 6), include Mida ($\varepsilon_i = 1.55$; $R_i = 1.47$) (KAZ); Sarvar ($\varepsilon_i = 0.64$; $R_i = 1.49$) (TJK); Yayla 302 ($\varepsilon_i = 1.48$; $R_i = 1.47$) (TUR); and Vanguard ($\varepsilon_i = 0.72$; $R_i = 1.52$) (USA). The standard Podolianka ($\varepsilon_i = 0.30$; $R_i = 0.94$) (UKR) was characterised by a sum of ranks of 4 regarding ecological plasticity. The identified high-yielding genotypes, which exhibit tolerance to the snow mould pathogen, provide a foundation for developing the most suitable and adaptive varieties based on them.

An analysis of the relationships between the studied traits revealed that, in soft winter wheat varieties, resistance to the snow mould pathogen (*Microdochium nivale* (Fr.) Samuels & I.C. Hallett) correlates negatively and significantly with the sum of ranks of the genotype effect and degree of yield plasticity, with a correlation coefficient of r=0.69. Additionally, the selection value and homeostasis regarding resistance to *M. nivale* (Fr.) Samuels & I.C. Hallett also correlated negatively and significantly with the sum of ranks (genotype effect and degree of yield plasticity), specifically: r = 0.68 and r = 0.56, respectively. The significance of these correlations was found to be 99% ($P < 0.01$) (Table 4).

***Table 4**. Correlation (r) of the sum of the ranks of the genotype effect and degree of yield plasticity in soft winter wheat varieties with adaptive parameters for resistance to Microdochium nivale (Fr.) Samuels & I.C. Hallett, 2020-2023*

Trait	The sum of ranks of genotype effect (ε_i) and degree of plasticity (R_i) for yield, t/ha
Resistance to *M. nivale* (Fr.) Samuels & I.C. Hallett, score	-0.69 $^{1)}$
Selection value for resistance to *M. nivale* (Fr.) Samuels & I.C. Hallett	-0.68 $^{1)}$
Homeostasis of resistance to *M. nivale* (Fr.) Samuels & I.C. Hallett, Hom	-0.56 $^{1)}$

Note: $^{1)}$ *– $P < 0.01$*

***Source:** compiled by the authors*

Thus, among the biotic factors that act as environmental stressors, the snow mould pathogen (*Microdochium nivale* (Fr.) Samuels & I.C. Hallett) has a significant negative impact on the potential and stability of yield in soft winter wheat varieties. This necessitates the compulsory inclusion of sources exhibiting high resistance to this phytopathogen in the breeding process. Based on the obtained research results, it can be asserted that within the genetic diversity of the studied soft winter wheat material, there exist genotypes characterised by a combination of high levels of resistance to *M. nivale* (Fr.) Samuels & I.C. Hallett, yield, and adaptability, among which varieties of Ukrainian selection predominate in terms of quantity. An extensive search for these sources, along with investigations into the correlations between environmental stress factors and the adaptive traits of soft winter wheat varieties, enables the identification of superior genetic material for selection focused on adaptability and helps determine priority approaches for developing well-adapted genotypes.

DISCUSSION

Several authors, including T. Yurchenko *et al.* (2020), note that the increased impact of various environmental stressors on the genetic yield potential and adaptive traits of soft winter wheat makes it necessary to conduct research aimed at determining ecological plasticity and stress resistance, which are a preliminary and mandatory stage for the selection of valuable genotypes as a necessary basis for selection for adaptability.

There are many aspects to the importance of factors that can influence the realisation of a high and stable yield genotype. Significant attention is paid to weather conditions (Parvez & Chowdhury, 2020). Researchers P. Langridge and M. Reynolds (2021) note that the main limiting factor that wheat plants suffer from in the environment is water deficit. Therefore, the identification and selection of highly effective sources and donors of drought resistance, through the use of wide genetic analysis strategies and modification of gene expression among diverse varieties, is the basis for identifying adapted genotypes for specific agroecological growing conditions.

Ukrainian scientists M.V. Tarasiuk and O.O. Stasik (2022), studying the impact of drought on the dynamics of accumulation and remobilisation of reserve water-soluble carbohydrates (WSC), which are an important source of assimilates for grain filling, established that the content of WSC in the second and lower internodes correlated most strongly and positively with grain weight per plant (r=0.534…0.693) and with the weight of 1000 grains (r=0.778…0.897). Iranian researchers S. Mahdavi *et al.* (2022), investigating 64 wheat genotypes under thermal stress caused by delayed sowing, concluded that thermal stress led to a significant reduction in grain density due to a decrease in starch content (SC) and a non-compensatory increase in protein content (PC), resulting in reduced yield. The researchers also noted a significant increase in the water absorption capacity of flour (WA), ash content (AC), lipid content (LC), wet gluten content (WG), dry gluten content (DG), gluten index (GI), and amylopectin content (APC) following thermal stress, which improved certain baking properties.

Researchers S.P. Lyfenko *et al.* (2021) argue that to increase the homeostasis of modern wheat varieties and their resistance to sudden abiotic stressors, it is necessary to create varieties with greater sensitivity to photoperiod and to include drought-tolerant material in breeding programs. Researchers X. Wu *et al.* (2021) emphasise the importance of introducing new varieties with reliable genetic protection against pathogens, which is associated with the undeniable economic and environmental advantages of alternative plant protection. Chinese scientists D.-X. Tang *et al.* (2022) note that a detailed study of the species composition and toxicity of common fungi of the genus *Microdochium* contributes to the effectiveness of selection for immunity and increased adaptability in new varieties.

Ukrainian scientists A.V. Pirych *et al.* (2021) indicate that a significant component of the overall adaptive potential of soft winter wheat is its winter hardiness, which is determined by a complex of traits that ensure plant survival during winter. These traits include frost resistance, duration of vernalisation, photoperiod sensitivity, and resistance to the pathogen causing snow mould. As a result of a targeted search by Ukrainian scientists for genotypes with high adaptive properties, soft winter wheat varieties have been identified that are characterised by increased yield potential and ecological plasticity to the agro-ecological conditions of the central Forest-Steppe of Ukraine – Estafeta Myronivska ta Hratsiia Myronivska, MIP Assol and Balada Myronivska.

In their study of new varieties of soft winter wheat across various soil and climatic zones in Ukraine, A.M. Kyrylchuk *et al.* (2024) identified genotypes with high homeostasis and low yield variability ($V \leqslant 10.0\%$), among which Yevraziia (Hom=15.6) and Dekaster (Hom=15.2) stood out as the best. The researchers noted that the varieties LG Optimist and Dekaster exhibited the highest selection value for yield – Sc=6.9 and Sc=6.6, respectively. Additionally, in their analysis of yield variability and quality parameters of *T. aestivum*, as well as their relationship with natural and anthropogenic factors, O. Demydov *et al.* (2022) established a significant ($P \leqslant 0.01$) influence of the growing period on the yield of this crop (66.2%), the mass of 1000 grains (63.2%), and grain density (58.8%).

Despite the variety of approaches to realising a high and stable yield genotype, several scientists, including T. Miedaner and P. Juroszek (2021), have concluded that due to the trend towards a changing climate towards global warming, droughts, which are becoming increasingly frequent, have a detrimental impact on the formation of yield levels and stability. Therefore, the identification and creation of material with simultaneous resistance to phytopathogens and water deficit is becoming increasingly relevant, while it is important to focus on quantitative trait loci (QTL) that reduce temperature sensitivity.

Thus, the results of determining the ecological plasticity of soft winter wheat varieties differentiated by resistance to the snow mould pathogen, establishing correlations between the sum of ranks of the genotypic effect and the degree of yield plasticity with the parameters of adaptability for resistance to *M. nivale* indicate the uniqueness of the study.

CONCLUSIONS

Based on the sum of ranks for genotype effect (ε_i) and the regression coefficient (R_i) for yield among soft winter wheat varieties differentiated by their resistance to the snow mould pathogen (*Microdochium nivale* (Fr.) Samuels & I.C. Hallett), genotypes have been identified that exhibit the highest genetic potential for adaptability. This is evidenced by the lowest sum of ranks (sum of ranks 2), which results in a yield exceeding the standard by more than 16%. The identified varieties include Muza Bilotserkivska ($\varepsilon_i = 1.14$; $R_i = 0.54$), Askaniiska Berehynia ($\varepsilon_i = 0.83$; $R_i = 0.56$), Hetmanska ($\varepsilon_i = 0.81$; $R_i = 0.31$), Malovanka ($\varepsilon_i = 0.71$; $R_i = 0.80$) (UKR), and Nordika ($\varepsilon_i = 0.99$; $R_i = 0.49$) (CZE), collectively accounting for 16.7%. The variety Svitiaz (sum of ranks 3) was slightly behind these, yet also exhibited a high yield with $\varepsilon_i = 1.39$ and $R_i = 0.88$. The lowest ecological plasticity, based on genotype effect and plasticity degree (sum of ranks 6), was observed in the varieties Mida ($\varepsilon_i = 1.55$; $R_i = 1.47$) (KAZ), Sarvar ($\varepsilon_i = 0.64$; $R_i = 1.49$) (TJK), Yayla 302 ($\varepsilon_i = 1.48$; $R_i = 1.47$) (TUR), and Vanguard ($\varepsilon_i = 0.72$; $R_i = 1.52$) (USA), which comprised 13.3% of the total research sample.

New sources of high and stable resistance in soft winter wheat to *M. nivale* (Fr.) have been identified, specifically: Sanzhara (Hom = 144.5), Malovanka

(Hom = 120.3), Svitiaz (Hom = 98.0), and Muza Bilotserkivska (Hom = 64.0) (UKR); Smuga (Hom = 64.0) (POL); and Nordika (Hom = 87.3) (CZE). It has been determined that among the soft winter wheat varieties differentiated by their resistance to *M. nivale* (Fr.) Samuels & I.C. Hallett, the genotype effect (ε_i) for yield ranged from 1.68 to 1.39, while the regression coefficient (R_i) varied from 0.22 to 1.78. This significantly influenced the level of ecological plasticity, with the sum of ranks ranging from 2 to 6. The proportion of samples exhibiting high values of the genotype effect constituted 43.3%, while those with high yield stability accounted for 36.7%. It was established that for the soft winter wheat varieties, resistance to *M. nivale* negatively correlated at a significant level with the sum of ranks for genotype effect and yield plasticity degree, with $r = 0.69$, $P < 0.01$.

The identified sources of high levels of group resistance to *M. nivale* (Fr.) Samuels & I.C. Hallett, high potential and yield stability expand the information content about the genetic diversity of existing varieties and open up additional opportunities in adaptive selection. The study of physiological and biochemical processes of adaptation, features of transcriptomics and proteomics in material with different ecological plasticity is promising for future research, which will open up more opportunities for generalising and systematising the results of the study.

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CONFLICT OF INTEREST

None.

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Екологічна пластичність сортів пшениці м'якої озимої та стійкість до збудника снігової плісняви (*Microdochium nivale* (Fr.) Samuels & I.C. Hallett)

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Анотація. Визначення кращих генотипів пшениці м'якої озимої з високою екологічною пластичністю до ґрунтово-кліматичних умов вирощування у поєднанні з толерантністю до поширених хвороб, спричинених грибними збудниками, в тому числі і снігової плісняви, набуває все більшої актуальності для виробництва та селекції, яка зумовлена попитом на світовому ринку екологічно-безпечної продукції. Попереднє виділення найбільш цінного вихідного матеріалу з високою стресостійкістю до періодичних змін у кліматі та погіршеного фітосанітарного стану передує успішності селекційного процесу щодо актуальних викликів сьогодення. Метою досліджень було визначення рівня екологічної пластичності в сортів пшениці м'якої озимої, диференційованих за стійкістю до збудника снігової плісняви, шляхом аналізу рангів генотипового ефекту та коефіцієнту регресії врожайності, а також виділення високоврожайних джерел для використання в селекції на адаптивність. Дослідження проведені згідно загальноприйнятих методик для оцінки матеріалу вивчення за стійкістю до збудників хвороб та адаптивних властивостей, які забезпечили інтерпретацію одержаних результатів високою об'єктивністю. Визначено, що найвищою екологічною пластичність серед диференційованого матеріалу вивчення за стійкістю до *Microdochium nivale* (Fr.) Samuels & I.C. Hallett відзначилися п'ять сортів (16,7 %), які вирізнялися формуванням врожайності від 118 % до 129 % до стандарту. До них відносяться сорти Муза білоцерківська, Асканійська берегиня, Гетьманська, Мальованка (UKR) та Nordika (CZE), про що свідчить найменша сума рангів (сума рангів 2) генотипового ефекту (ε_i) та коефіцієнту регресії (R_i). Виділено нові джерела високої та стабільної стійкості пшениці м'якої озимої до збудника снігової плісняви, а саме: Санжара, Мальованка, Світязь, Муза білоцерківська (UKR); Smuga (POL) та Nordika (CZE). Встановлено, що у сортів пшениці м'якої озимої стійкість до *Microdochium nivale* (Fr.) Samuels & I.C. Hallett на значному негативному рівні корелює із сумою рангів генотипового ефекту і ступеня пластичності врожайності – $r = -0,69$, $P < 0,01$. Систематизація отриманих результатів вивчення, виділення сортів з найвищою екологічною пластичністю в мінливих погодних умовах агроекологічної зони, дають можливість ідентифікувати кращий генофонд для адаптивної селекції

Ключові слова: адаптивність; гомеостатичність; епіфітотії; генотиповий ефект; мінливість; урожайність