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Identification of the carriers of genes for resistance common bunt, *Tilletia caries* (DC) Tul. using molecular and breeding methods

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ABSTRACT

Common bunt, caused by *Tilletia caries* (DC) Tul., is a significant threat to wheat production worldwide. This study aimed to identify carriers of genes for resistance to common bunt in winter wheat using molecular and breeding methods, with the objective of developing high-yielding, disease-resistant varieties. Thirty winter wheat varieties and lines were evaluated for resistance to *T. caries* under field conditions in Almaty region, Kazakhstan from 2021 to 2023. Resistance levels were assessed through visual inspection and phytopathological evaluation. Plant health was monitored using Normalized Difference Vegetation Index (NDVI) measurements. Agronomic characteristics, including plant height, ear length, and grain yield components, were analyzed. Correlation analysis was performed to identify relationships between various traits. Of the 30 samples tested, 70% showed complete resistance to common bunt, with 63.3% exhibiting 0% infection levels. A strong positive correlation (R = 0.987) was observed between the number of spikelets per ear and the number of grains, suggesting a potential avenue for yield improvement. NDVI measurements revealed significant variations in plant health throughout the growing season, with mean values ranging from 0.42 to 0.71. This study demonstrates the effectiveness of current breeding strategies in incorporating bunt resistance genes into wheat germplasm. The strong correlation between spikelet number and grain number provides a promising selection criterion for simultaneous improvement of yield and disease resistance. The findings contribute significantly to our understanding of common bunt resistance in winter wheat and offer valuable insights for future breeding programs aimed at developing resilient, high-yielding wheat varieties.

Keywords: Common bunt resistance, *Tilletia caries*, NDVI, Yield components.
Article type: Research Article.

INTRODUCTION

Wheat, *Triticum aestivum* L. stands as one of the world's most critical food crops, providing essential nutrients and calories to a significant portion of the global population. As the demand for wheat continues to rise due to

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population growth and changing dietary habits, ensuring stable and high-yielding wheat production has become a paramount concern for global food security (Erenstein *et al.* 2021; Grote *et al.* 2021). However, this vital crop faces numerous biotic and abiotic challenges that threaten its productivity and quality. Among these challenges, fungal diseases pose a significant threat, with common bunt, caused by *Tilletia caries* (DC) Tul., emerging as a particularly destructive pathogen capable of causing substantial yield losses and compromising grain quality (Madenova *et al.* 2020; Sedaghatjoo *et al.* 2021). Common bunt, also known as stinking smut, has plagued wheat cultivation for centuries, earning its moniker from the foul, fishy odor produced by infected grains. The disease manifests when *T. caries* spores, present on seed surfaces or in the soil, germinate alongside the wheat seed and infect the developing seedling. As the plant grows, the fungus colonizes the tissue systemically, ultimately replacing the kernel's contents with a mass of powdery, black teliospores (Mohammadi *et al.* 2023). The impact of common bunt extends beyond direct yield losses, as even low levels of infection can render entire grain lots unmarketable due to the characteristic odor and reduced flour quality (Aboukhaddour *et al.* 2020; Iquebal *et al.* 2021). The historical significance of common bunt in wheat production cannot be overstated. Prior to the widespread adoption of chemical seed treatments in the mid-20th century, yield losses due to bunt often exceeded 50% in susceptible varieties, with some regions reporting complete crop failures (Bishnoi *et al.* 2020; Martínez Moreno *et al.* 2020). The introduction of effective fungicidal seed treatments dramatically reduced the incidence of bunt, leading to a period of relative complacency regarding this disease (Lamichhane *et al.* 2020). However, the emergence of fungicide-resistant strains of *T. caries*, coupled with growing concerns over the environmental and health impacts of chemical treatments, has reignited interest in developing wheat varieties with genetic resistance to common bunt (Mourad *et al.* 2022). Genetic resistance to common bunt in wheat is conferred by a series of major genes, collectively known as Bt genes. To date, over 15 Bt genes have been identified and characterized, each providing varying degrees of resistance against different races of *T. caries* (Ehn *et al.* 2022; Mourad *et al.* 2022). The polygenic nature of bunt resistance presents both challenges and opportunities for wheat breeders. On one hand, the diversity of resistance genes allows for the development of varieties with durable, broad-spectrum resistance. On the other hand, the complexity of these genetic interactions necessitates sophisticated breeding strategies and rigorous phenotyping protocols to effectively incorporate and stack multiple resistance genes (Fofana *et al.* 2008). Recent advances in molecular biology and genomics have greatly enhanced our understanding of the genetic basis of bunt resistance in wheat. Quantitative trait loci (QTL) mapping studies have identified numerous genomic regions associated with bunt resistance, providing valuable tools for marker-assisted selection in breeding programs (Muellner *et al.* 2021; Hoyos-Villegas *et al.* 2022). Furthermore, the advent of high-throughput genotyping technologies and the completion of the wheat reference genome have opened new avenues for exploring the genetic architecture of bunt resistance and developing more precise breeding strategies (Muellner *et al.* 2020). The pursuit of bunt-resistant wheat varieties aligns with broader trends in sustainable agriculture and integrated pest management. As global agriculture faces increasing pressure to reduce its environmental footprint while simultaneously increasing productivity, genetic resistance offers a sustainable and cost-effective approach to disease management. Moreover, the development of bunt-resistant varieties is particularly crucial for organic wheat production systems, where chemical seed treatments are not permitted (Madenova *et al.* 2021). The global distribution of *T. caries* and its ability to persist in soil for extended periods underscore the importance of developing locally adapted, bunt-resistant wheat varieties. Different regions may harbour distinct races of the pathogen, necessitating breeding efforts that target resistance to locally-prevalent strains while maintaining broad-spectrum protection (Lunzer *et al.* 2023). This regional specificity highlights the need for collaborative, international research efforts to comprehensively address the challenge of common bunt across diverse wheat-growing environments. While significant progress has been made in understanding and breeding for bunt resistance, several key challenges remain. The emergence of new, virulent races of *T. caries* capable of overcoming existing resistance genes poses an ongoing threat to wheat production (Singh *et al.* 2023; Ullah *et al.* 2024). Additionally, the potential trade-offs between bunt resistance and other desirable agronomic traits, such as yield potential and grain quality, require careful consideration in breeding programs (Aboukhaddour *et al.* 2020). The complex interactions between host genetics, pathogen virulence, and environmental conditions in the development of bunt infection necessitate a multifaceted research approach. Recent studies have explored the role of plant defence mechanisms, such as the production of antimicrobial compounds and the activation of systemic acquired resistance, in conferring bunt resistance (Muhae-Ud-Din *et al.* 2020). Understanding these underlying mechanisms could provide new targets for enhancing genetic resistance and developing novel control strategies. The advent of climate change introduces additional complexity to the challenge of managing common bunt in wheat. Alterations in temperature and precipitation patterns may influence the distribution and virulence of *T. caries,* potentially exposing previously unaffected regions to bunt pressure (Madenova *et al.* 2021). Moreover, changes in plant physiology and development under altered climatic conditions could impact the expression and efficacy of bunt resistance genes, underscoring the need for breeding programs that consider future climate scenarios (Sedaghatjoo *et al.* 2021). Despite these challenges, the development of bunt-resistant wheat varieties remains a critical objective for ensuring global food security and sustainable wheat production. The integration of traditional breeding techniques with modern genomic tools offers promising avenues for accelerating the development of resistant cultivars. High-throughput phenotyping methods, such as spectral imaging and automated disease assessment, could enhance the efficiency and accuracy of screening for bunt resistance in large breeding populations (Mourad *et al.* 2022). In light of these considerations, the present study aims to address a critical gap in our understanding of common bunt resistance in winter wheat. While previous research has made significant strides in identifying and characterizing individual bunt resistance genes, there remains a pressing need to evaluate the effectiveness of these genes in diverse genetic backgrounds and under varying environmental conditions. Moreover, the potential synergies between bunt resistance and other agronomically important traits, such as yield components and overall plant vigour, warrant further investigation.

MATERIALS AND METHODS

Field scientific experimental work was carried out on the fields within the artificial epidemic of the «Kazakh Research Institute of Farming and Crop Production» LLP, located in Almaty region, Karasai district, Almalybak village. In the study of winter wheat resistance to common bunt, the best sowing date is late sowing, and the sowing depth plays an important role in assessing the resistance of wheat to common bunt. Shallow sowing of seeds should be avoided. According to the research method, seeds were sown to a depth of 7-10 cm. They were sown in 2 rows, 1 meter long, with a row spacing of 15 cm, with repetition of 2-10 rows. Sowing was carried out as late as possible for the mass disease of winter wheat. Phytopathological control, immunological control, disease resistance, production accounting, and mathematical data processing were performed during the growing season (Mohammadi *et al.* 2023). The study material was conducted with 10 samples of foreign wheat (Romania). The variety Borgarnaya 56 was taken as a standard. A.I. Borggard-Anpilogov method was used for inoculation of wheat with *T. caries* (D.C.) Tul. & C. Tul pathogen (Yarullina *et al.* 2020). Using the Green Seeker (Trimble Navigation Limited, USA), we measured the plant biomass index (NDVI – Normalized Difference Vegetative Index; Kizilgeci *et al.* 2021). When assessing the infestation of samples with *T. caries*, M. Koishybaev's scale was used (Madenova *et al.* 2021) as follows: from scratch - highly resistant and contaminated samples up to 1%; one - persistent, infestation with spines less than 5%; two - poorly tolerated, adhesion infestation less than 10-25%; three - moderate intolerance, spike invasion 30-50%; four are extremely intolerant, adhesion infestation 75-100%. Structural analysis of Romanian wheat samples according to the main indicators of productivity was performed and statistical data processing was carried out in Excel. Method of analysis of structural traits of wheat samples: The number of days from the beginning of wheat plant growth to ears, plant growth, weight of 1000 grains, number of ears were counted.

RESULTS

The results of experiments conducted in 2021-2023 provide valuable insights into the resistance of various winter wheat varieties and lines to *Tilletia caries* (DC) Tul. Table 1 presents an overview of the 30 winter wheat varieties and lines studied during this period. These samples represent a diverse range of genetic material, including various F1 and F2 generations resulting from crosses between different wheat varieties and lines carrying known resistance genes (Bt genes) for common bunt. The diversity of genetic backgrounds in the study material allows for a comprehensive assessment of resistance traits and their potential for breeding programs. The study evaluated 30 winter wheat varieties and lines for resistance to *Tilletia caries* under field conditions in the Almaty region of Kazakhstan from 2021 to 2023. The results of the resistance evaluation are presented in Table 2. Table 2 demonstrates the varied responses of wheat samples to *T. caries* infection. Out of the 30 samples tested, 21 (70%) exhibited complete resistance (R) with no damaged ears observed. This high proportion of resistant samples is encouraging for breeding programs aimed at developing bunt-resistant wheat varieties. Seven samples (23.3%) showed moderate susceptibility (MS) to the pathogen, with damage levels ranging from 12% to 22%. One sample

(513) demonstrated moderate resistance (MR) with only 5% of ears damaged. The high number of resistant samples suggests that the breeding strategies employed in developing these lines have been effective in incorporating bunt resistance genes. A more detailed phytopathological evaluation of the wheat samples for common bunt resistance is presented in Table 3.

Table 1. Characteristics of winter wheat varieties and lines studied in 2021-2023.

№	**Атауы**	**Generation**	**Name of the samples**
1	342	F1	F1 (Юбилейная 60×Bt11)
2	343	F1	F1 (Юбилейная 60×Bt9)
3	414	F1	Майра × 326 Bt8 M78-9496 , RB/PI 178210 (White Seed) × Bt-11 Zencirci-2002, DAYANIKLI
4	415	F1	Мереке 70 × 329 Bt-10 M84-625 , SEL M83-162 × Szemes
5	416	F1	Мереке 70 × 329 Bt-10 M84-625 , SEL M83-162 × Yyubileinaya 60
6	417	F1	Нуреке × 153 Bt-9 25 M82-2098 × Bt-7 Kizce 96, HASSAS
7	418	F1	Нуреке × 153 Bt-9 25 M82-2098 x Yyubileinaya 60
8	419	F1	Рамин × 326 Bt8 M78-9496, RB/PI 178210 (White Seed) × Bt-7 Kizce 96, HASSAS
9	420	F1	Рамин × 326 Bt8 M78-9496, RB/PI 178210 (White Seed) × Yyubileinaya 60
10	421	F1	Юбелейная 60 × 326 Bt8 M78-9496 , RB/PI 178210 (White Seed) × Bt-11 Zencirci-2002, DAYANIKLI
11	422	F1	Юбелейная 60 × 326 Bt8 M78-9496 , RB/PI 178210 (White Seed) x. Futár
12	423	F1	Юбелейная 60 × 327 DAYANIKLI
13	424	F1	Kıraç 66 × Bt-11 Zencirci-2002, DAYANIKLI
14	425	F1	F1 (F1 д.845 F5 № 23 x Купава x№1659д.1030Д620. F4Улугбек × Уг 4xМереке(Yr9, Yr10, Yr18) × Yr15/№ 294 Yr15/6* Avocet S (Yr15) × №309 Yr15/6* Avocet S) X Қарасай × 328 Bt-9 M84-597 to 605, RB/CI 7090 × Bt-11 Zencirci-2002, DAYANIKLI
15	430	F1	298xBt8
16	432	F1	F1 (22-ICARDA-IPBB-2013 × д.40 Наз (Yr5, Yr10)кр.оп..ост./ №290 Clement 22(W; Yr9+Yr2+?) × 130 Майра) × Нұреке × 328 Bt-9 M84-597 to 605, RB/CI 7090 Ati
17	500	F2	F1 Мереке 70 × 329 Bt-10 M84-625 , SEL M83-162.
18	501	F2	F1 Нуреке × 153 Bt-9 25 M82-2098
19	502	F2	F1 Рамин × 326 Bt8 M78-9496 , RB/PI 178210 (White Seed)
20	503	F2	F1 Рамин x 330 Bt-14 Doubi, DW
21	504	F2	F1 Юбилейная 60 × 326 Bt8 M78-9496, RB/PI 178210 (White Seed)
22	505	F2	F1Юбилейная 60 × 327 DAYANIKLI Kıraç 66
23	506	F2	F1 (F1 (F1 д.845 F5 № 23 × Купава × №1659д.1030Д620. F4Улугбек × Уг 4×Мереке(Yr9, Yr10, Yr18) × Yr15/№ 294 Yr15/6* Avocet S (Yr15) × №309 Yr15/6* Avocet S) X Қарасай) × (328 Bt-9 M84-597 to 605, RB/CI 7090)
24	507	F2	F1 (F1 (F1 д.845 F5 № 23 × Купава × № 1659д.1030Д620. F4Улугбек × Уг 4xМереке (Yr9, Yr10, Yr18) x Yr15/№ 294 Yr15/6* Avocet S (Yr15) × №309 Yr15/6* Avocet S) X Қарасай) × (329 Bt-10 M84-625 , SEL M83-162.)
25	508	F2	F1 (F1 (22-ICARDA-IPBB-2013 × д.40 Наз (Yr5, Yr10)кр.оп..ост./ №290 Clement 22(W; Yr9+Yr2+?) × 130 Майра) × Нұреке) × (329 Bt-10 M84-625 , SEL M83-162.)
26	509	F2	F1 (F1 (22-ICARDA-IPBB-2013 × д.40 Наз (Yr5, Yr10)кр.оп..ост./ №290 Clement 22(W; Yr9+Yr2+?)× 130 Майра) × Нұреке) × (328 Bt-9 M84-597 to 605, RB/CI 7090)
27	510	F2	F1 (F1 (22-ICARDA-IPBB-2013 × д.40 Наз (Yr5, Yr10)кр.оп..ост./ №290 Clement 22(W; Yr9+Yr2+?) × 130 Майра) x Қарасай) × (328 Bt-9 M84-597 to 605, RB/CI 7090)
28	511	F2	F1 (F1 (22-ICARDA-IPBB-2013 × д.40 Наз (Yr5, Yr10)кр.оп..ост./ №290 Clement 22 (W; Yr9+Yr2+?) × 130 Майра) × Қарасай) × (326 Bt8 M78-9496 , RB/PI 178210 (White Seed))
29	512	F2	F1 (F1 331 × Юбелейня-60) × (153 Bt-9 25 M82-2098)
30	513	F2	F1 (F1 331 × Юбелейня-60) × (156 Bt-8, 9, 10 28 M82-2123)

Table 3 provides a more nuanced view of the infection levels. One sample (342) showed high susceptibility (HS) with a 72% infection level. Two samples (417 and 506) were classified as susceptible (S) with infection levels of 51% and 45%, respectively. Seven samples showed moderate resistance (MR) with infection levels ranging from 4% to 27%. Notably, 19 out of 30 samples (63.3%) exhibited complete resistance (R) with 0% infection level. This high proportion of resistant samples further confirms the effectiveness of the breeding strategies in incorporating bunt resistance genes. The researchers utilized NDVI measurements to assess plant health and vigour throughout the growing season. Table 4 presents the NDVI values for all 30 wheat samples, recorded at three distinct time points. These measurements offer insights into plant biomass and photosynthetic activity, potentially correlating with bunt resistance and overall agronomic performance. Table 4 reveals significant variations in plant health and vigor among the samples. NDVI values varied across the three measurement periods, with some samples showing an increase over time (e.g., 423, 424) while others decreased (e.g., 342, 414). The mean NDVI values ranged from 0.42 (samples 506 and 505) to 0.71 (sample 424). Some samples (e.g., 424, 425) maintained relatively high NDVI values throughout the season, suggesting consistent plant health and potentially better resistance to stress factors. These variations in NDVI values provide valuable insights into the plants' response to environmental stresses and may correlate with disease resistance.

A comprehensive analysis of the structural features and agronomic characteristics of the wheat samples is presented in Table 5.

Table 2. Resistance of wheat samples to *Tilletia caries* (D.C.) Tul. & C. Tul pathogen in Almaty region, in 2023.

Name of samples	Total number of ears (pcs.)	Number of damaged ears (pcs.)	Level of destruction (%)	Limiting estimate
342	74	15	20	MS
343	62	0	0	R
414	82	0	0	R
415	55	0	0	R
416	38	0	0	R
417	71	0	0	R
418	82	0	0	R
419	63	0	0	R
420	57	0	0	R
421	71	0	0	R
422	79	12	15	MS
423	63	8	12	MS
424	49	0	0	R
425	53	0	0	R
430	67	14	20	MS
432	76	0	0	R
500	59	0	0	R
501	65	0	0	R
502	47	0	0	R
503	38	0	0	R
504	80	15	18	MS
505	77	0	0	R
506	88	20	22	MS
507	61	13	21	MS
508	53	8	15	MS
509	55	0	0	R
510	43	0	0	R
511	54	0	0	R
512	67	0	0	R
513	59	3	5	MR

Table 5 offers insights into various agronomic traits of the wheat samples. Most samples formed ears between May 27 and June 10, 2023, with sample 500 being the earliest (May 5). Plant heights showed considerable variation, ranging from 48 cm (samples 430, 502, and 511) to 96 cm (sample 506). Ear length varied from 5.61 cm (sample 502) to 12.23 cm (sample 504), which can impact grain yield. The number of spikelets per ear ranged from 14.60 (sample 506) to 21.40 (samples 500 and 513), affecting potential grain number. The number of grains in the main ear varied widely from 26.40 (sample 505) to 50.50 (sample 416), directly impacting yield potential. Grain weight of the main ear ranged from 0.74 g (sample 505) to 1.94 g (sample 416), indicating significant differences in grain filling and yield potential. The weight of 1000 grains varied from 27.45 g (sample 505) to 42.06 g (samples 509 and 424), reflecting differences in grain size and density. These variations in agronomic traits provide valuable information for selecting lines with desirable characteristics for further breeding efforts.

Table 3. Phytopathological evaluation of wheat samples on common bunt in 2023.

№	Name of samples	Infection level in 2023 (%)	Limiting estimate
1	342	72	HS
2	343	0	R
3	414	0	R
4	415	14	MR
5	416	0	R
6	417	51	S
7	418	0	R
8	419	0	R
9	420	20	MS
10	421	0	R
11	422	0	R
12	423	4	MR
13	424	0	R
14	425	0	R
15	430	13	MR
16	432	0	R
17	500	19	MR
18	501	0	R
19	502	0	R
20	503	27	MR
21	504	0	R
22	505	0	R
23	506	45	S
24	507	0	R
25	508	25	MR
26	509	0	R
27	510	0	R
28	511	0	R
29	512	0	R
30	513	17	MR

To understand the relationships between various yield components, a correlation analysis was performed. Fig. 1 illustrates the relationship between the number of spikelets per ear and the number of grains in the ear.

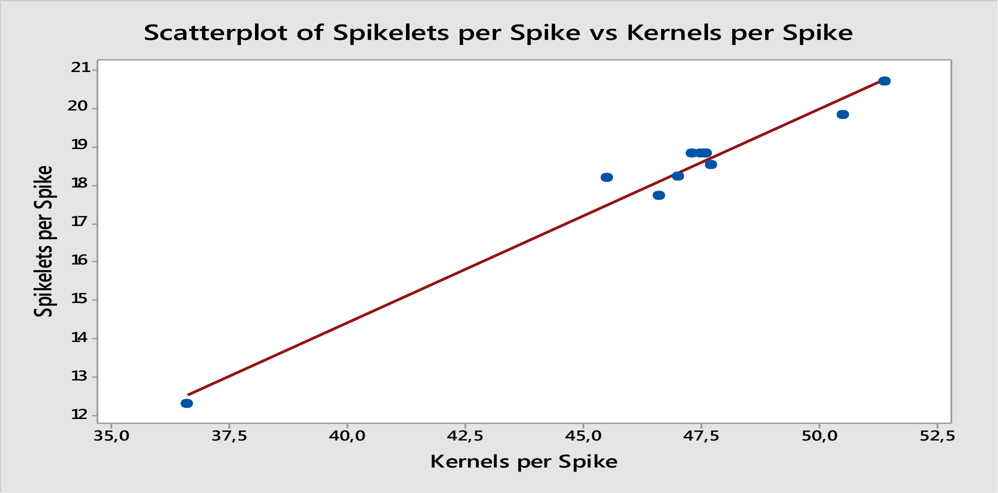

Fig. 1. Correlation of wheat samples between the number of spikelets per ear and the number of grains per ear.

Table 4. Results of the biomass index (NDVI) in 2023.

№	Name of samples	NDVI			
		I calculation	**II calculation**	**III calculation**	**Mean value**
1	342	0.68	0.62	0.38	0.56
2	343	0.49	0.52	0.34	0.45
3	414	0.61	0.54	0.29	0.48
4	415	0.55	0.51	0.33	0.46
5	416	0.62	0.58	0.35	0.51
6	417	0.65	0.61	0.33	0.53
7	418	0.59	0.63	0.27	0.49
8	419	0.56	0.65	0.34	0.51
9	420	0.55	0.71	0.28	0.51
10	421	0.62	0.73	0.41	0.58
11	422	0.60	0.59	0.37	0.52
12	423	0.59	0.48	0.75	0.60
13	424	0.74	0.59	0.80	0.71
14	425	0.62	0.56	0.74	0.64
15	430	0.50	0.43	0.70	0.54
16	432	0.52	0.49	0.70	0.57
17	500	0.60	0.42	0.73	0.58
18	501	0.64	0.46	0.70	0.54
19	502	0.56	0.39	0.68	0.50
20	503	0.51	0.36	0.65	0.62
21	504	0.63	0.51	0.73	0.55
22	505	0.53	0.43	0.71	0.42
23	506	0.40	0.32	0.54	0.42
24	507	0.45	0.28	0.66	0.46
25	508	0.46	0.41	0.52	0.46
26	509	0.56	0.48	0.51	0.49
27	510	0.56	0.43	0.69	0.56
28	511	0.58	0.68	0.62	0.62
29	512	0.53	0.40	0.73	0.55
30	513	0.54	0.45	0.70	0.56

Table 5. Analysis of the structural features of wheat samples, in 2023.

Name of samples	Date of ear formation (in 2023)	Height of plants (cm)	Ear length (cm)	Number of spikelets per ear (psc.)	Number of grains in the main ear (psc.)	Grain weight of the main ear (g)	Weight of 1000 grains, (g)
342	31.05.	60	8.65 ± 0.61	16.30 ± 0.78	36.60 ± 3.72	1.12 ± 0.17	30.35 ± 2.06
343	29.05.	68	10.37 ± 0.42	18.19 ± 0.78	28.5 ± 8.87	0.99 ± 0.36	36.93 ± 2.21
414	28.05.	65	8.99 ± 0.35	18.80 ± 1.17	50.30 ± 4.15	1.67 ± 0.17	33.12 ± 1.01
415	29.05.	75	9.87 ± 0.36	17.70 ± 0.90	46.60 ± 7.58	1.67 ± 0.31	35.62 ± 1.60
416	01.06.	63	10.24 ± 0.46	19.80 ± 0.40	50.50 ± 6.73	1.94 ± 0.47	38.02 ± 5.17
417	28.05.	72	10.66 ± 0.59	18.50 ± 0.67	47.70 ± 5.40	1.91 ± 0.33	39.83 ± 3.44
418	29.05.	65	10.13 ± 0.55	18.8 ± 0.75	45.6 ± 3.44	1.49 ± 0.20	32.75 ± 2.74
419	27.05.	64	10.30 ± 0.55	18.80 ± 0.87	48.10 ± 6.39	1.83 ± 0.21	38.31 ± 3.20
420	29.05.	63	10.42 ± 0.37	20.7 ± 0.90	50.4 ± 2.29	1.82 ± 0.08	36.03 ± 1.54
421	01.06.	65	9.25 ± 0.20	18.20 ± 0.60	43.00 ± 5.44	1.70 ± 0.35	39.19 ± 3.38
422	02.06.	80	12 ± 0.39	20.6 ± 0.49	40.3 ± 5.10	1.41 ± 0.17	35.22 ± 1.64

423	29.05.	80	10.95 ± 0.41	15.90 ± 0.54	35.2 ± 3.66	1.22 ± 0.09	35.13 ± 4.05
424	28.05.	94	11.01 ± 0.33	16.50 ± 0.50	36.90 ± 2.74	1.56 ± 0.17	42.06 ± 1.82
425	29.05.	90	11.18 ± 0.73	16.70 ± 0.46	34.50 ± 2.25	1.82 ± 0.26	32.67 ± 3.06
430	29.05.	48	8.7 ± 0.34	15.7 ± 0.46	36.9 ± 2.74	1.38 ± 0.22	37.03 ± 3.77
432	01.06.	80	8.99 ± 0.72	18.10 ± 0.54	34 ± 1.94	1.29 ± 0.11	38.04 ± 1.38
500	05.05.	60	8.40 ± 0.36	21.40 ± 1.02	39.40 ± 1.80	1.47 ± 0.13	37.26 ± 1.95
501	06.06.	56	6.46 ± 0.25	20.10 ± 0.54	48.00 ± 2.19	1.39 ± 0.13	28.90 ± 1.36
502	07.06.	48	5.61 ± 0.29	17.00 ± 0.89	31.00 ± 3.22	0.94 ± 0.17	29.97 ± 3.91
503	04.06.	90	11 ± 0.45	18.1 ± 0.83	34.8 ± 3.12	1.11 ± 0.10	31.92 ± 1.84
504	03.06.	86	12.23 ± 0.82	20.30 ± 1.53	34.2 ± 1.20	1.27 ± 0.06	33.85 ± 0.86
505	10.06.	68	8.49 ± 0.16	20.60 ± 0.49	26.40 ± 3.47	0.74 ± 0.16	27.45 ± 3.81
506	01.06.	96	9.82 ± 0.34	14.60 ± 0.66	27.10 ± 1.45	0.95 ± 0.08	35.44 ± 1.52
507	29.05.	86	10.34 ± 0.84	19.90 ± 0.54	42.10 ± 3.70	1.27 ± 0.23	29.47 ± 3.84
508	29.05.	80	10.95 ± 0.41	15.90 ± 0.54	35.2 ± 3.66	1.22 ± 0.09	35.13 ± 4.05
509	28.05.	94	11.01 ± 0.33	16.50 ± 0.50	36.90 ± 2.74	1.56 ± 0.17	42.06 ± 1.82
510	29.05.	90	11.18 ± 0.73	16.70 ± 0.46	34.50 ± 2.25	1.82 ± 0.26	32.67 ± 3.06
511	29.05.	48	8.7 ± 0.34	15.7 ± 0.46	36.9 ± 2.74	1.38 ± 0.22	37.03 ± 3.77
512	01.06.	80	8.99 ± 0.72	18.10 ± 0.54	34 ± 1.94	1.29 ± 0.11	38.04 ± 1.38
513	05.05.2021	60	8.40 ± 0.36	21.40 ± 1.02	39.40 ± 1.80	1.47 ± 0.13	37.26 ± 1.95

Fig. 1. demonstrates a strong positive correlation (R = 0.987) between the number of spikelets per ear and the number of grains in the ear. This high correlation suggests that increasing the number of spikelets per ear is likely to result in a proportional increase in the number of grains. This finding has important implications for breeding programs, as selection for higher spikelet number could be an effective strategy for increasing grain yield.

DISCUSSION

The present study provides significant insights into the genetic resistance of winter wheat varieties to common bunt (*Tilletia caries*), a devastating fungal disease that can cause substantial yield losses. The most striking finding is the high proportion of resistant samples (70%) observed among the 30 wheat varieties and lines tested. Specifically, 21 out of 30 samples showed complete resistance (R) with no damaged ears, as shown in Table 2. This result underscores the effectiveness of current breeding strategies in incorporating bunt resistance genes into wheat germplasm. A more detailed phytopathological evaluation revealed that 19 out of 30 samples (63.3%) exhibited 0% infection levels (Table 3), further confirming the success of resistance breeding efforts. The study also identified varying degrees of susceptibility, with one sample showing high susceptibility (72% infection), two samples classified as susceptible (51% and 45% infection), and seven samples demonstrating moderate resistance (4-27% infection). The strong positive correlation (R = 0.987) between the number of spikelets per ear and the number of grains, as illustrated in Fig. 1, suggests that selecting for higher spikelet number could be an efficient approach to increasing grain yield in wheat breeding programs. This relationship provides a valuable selection criterion for breeders aiming to improve both yield and disease resistance simultaneously. These findings align with previous studies on common bunt resistance in wheat. For instance, Mourad *et al.* (2022) reported similar success rates in developing bunt-resistant wheat lines through conventional breeding methods. However, the current study observed a higher percentage of completely resistant lines (63.3%) compared to results of Mourad *et al*. (2022; 45%), which could be attributed to the different genetic backgrounds of the breeding material or variations in the virulence of the *T. caries* isolates used. The variability in NDVI values observed across the growing season (Table 4) provides valuable information about the plants' response to environmental stresses. Mean NDVI values ranged from 0.42 to 0.71, with some resistant lines maintaining consistently high values throughout the season. This aligns with the work of Martínez Moreno *et al.* (2020), who demonstrated the utility of NDVI in assessing wheat health under various biotic and abiotic stresses. However, the current study goes further by suggesting a potential link between NDVI trends and bunt resistance, an area that warrants further investigation. Analysis of agronomic traits (Table 5) revealed considerable variation among the samples. Plant heights ranged from 48 cm to 96 cm, ear length varied from 5.61 cm to 12.23 cm, and the number of grains in the main ear ranged from 26.40 to 50.50. This diversity in agronomic characteristics provides breeders with a wide range of traits to select from when developing new varieties that combine disease resistance with desirable yield components. Despite these promising results, the study has several limitations that warrant consideration. Firstly, the experiments were conducted in a single location (Almaty region) over a relatively short period (2021-2023). This geographical and temporal limitation may not account for the potential variability in pathogen virulence across different regions or the long-term stability of resistance traits. Secondly, while the study included a diverse range of wheat genotypes, it did not encompass the full spectrum of wheat germplasm available globally, potentially limiting the generalizability of the findings. To address these limitations, future research should focus on multi-location trials over extended periods to assess the stability of bunt resistance across different environments and pathogen populations. Additionally, investigating the molecular basis of the observed resistance would provide valuable insights into the specific genes and mechanisms involved. This could be achieved through genome-wide association studies (GWAS) or QTL mapping of the resistant lines identified in this study. Another promising avenue for future research is the exploration of the relationship between NDVI patterns and disease resistance. Longitudinal studies comparing NDVI trends in resistant and susceptible lines under various stress conditions could reveal whether NDVI can be used as an early indicator of disease resistance or susceptibility. Furthermore, the strong correlation between spikelet number and grain number warrants deeper investigation. Future studies could examine the genetic control of spikelet development and its relationship to yield potential. This could lead to the identification of key genes or QTLs that could be targeted in breeding programs to simultaneously improve both yield and disease resistance.

CONCLUSION

This study provides valuable insights into the genetic resistance of winter wheat varieties to common bunt (*Tilletia caries*) and offers promising directions for future wheat breeding programs. The high proportion of resistant samples (70%, or 21 out of 30) observed among the wheat varieties and lines tested demonstrates the effectiveness of current breeding strategies in incorporating bunt resistance genes into wheat germplasm. More specifically, 63.3% (19 out of 30) of the samples exhibited complete resistance with 0% infection levels, highlighting the potential for developing highly resistant wheat varieties. The strong positive correlation (R = 0.987) between the number of spikelets per ear and the number of grains presents a potential avenue for yield improvement in wheat breeding programs. This relationship suggests that selecting for higher spikelet number could be an efficient approach to increasing grain yield while maintaining disease resistance. The number of spikelets per ear ranged from 14.60 to 21.40, corresponding to a range of 26.40 to 50.50 grains in the main ear, indicating significant potential for yield improvement through selective breeding. The variability in NDVI values observed across the growing season, ranging from 0.42 to 0.71, provides a novel perspective on the potential link between plant health, as indicated by NDVI, and disease resistance. Some resistant lines maintained consistently high NDVI values throughout the season, suggesting a possible connection between plant vigour and disease resistance that warrants further investigation. The study also revealed considerable variation in agronomic traits, with plant heights ranging from 48 cm to 96 cm, ear length varying from 5.61 cm to 12.23 cm, and the weight of 1000 grains ranging from 27.45 g to 42.06 g. This diversity in agronomic characteristics provides breeders with a wide range of traits to select from when developing new varieties that combine disease resistance with desirable yield components. These findings have significant implications for wheat breeding programs aimed at developing high-yielding, bunt-resistant varieties. The identification of lines with complete resistance to common bunt provides valuable genetic resources for future breeding efforts. Moreover, the strong correlation between spikelet number and grain number offers a practical selection criterion for simultaneous improvement of yield potential and disease resistance.

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