



Effect of Fusarium infection on wheat quality parameters

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Abstract

Wheat is one of the most important cereal grains; it provides carbohydrate staple foods that form the basis of most diets around the world. Wheat production is endangered by *Fusarium species* which cause Fusarium head blight. Fusarium head blight is one of the most devastating diseases of small grain cereals. This disease not only causes grain yield losses, but also decreases wheat quality and causes the presence of harmful mycotoxins. The experiment was conducted during two growing seasons 2020 and 2021 at the experimental field and laboratories of the Hungarian University of Agriculture and Life Sciences (MATE). The aim of our study is to test the effect of Fusarium infection on wheat quality parameters. The wheat variety used in the experiment is Mv Kolompos. The results indicate that Fusarium infection in 2021 (94%) is higher than in 2020 (48.4%). The increase in Fusarium infection reduces wheat quality. Hence, it negatively affects protein content, test weight, thousand kernel weight, falling number, gluten content and Zeleny sedimentation index. The higher the Fusarium infection the lower the value of wheat quality parameters.

Keywords Wheat · Fusarium · Test weight and thousand kernel weight · Falling number · Zeleny sedimentation index · Protein and gluten content

Introduction

Cereals have been a basic agricultural product since ancient times due to their nutritional properties, moderate cost and ability to achieve immediate satiation. Wheat is a plant grown on more land area than any other commercial crop. Wheat provides carbohydrate staple foods that form the basis of most diets, both ancient and modern, around the world (Jones et al. 2015). Wheat flour is used in a diverse range of end use products including bread, cake, noodle, cracker, cookie, and pasta (Khan 2019). Wheat kernel is composed of endosperm (81–84%), bran (14–16%) and germ (2–3%). The endosperm is rich in carbohydrate, lipid and protein (Hung 2016). The bran is the outer layer protecting the kernel. The germ is the kernel's embryo that will grow into a new plant (Shewry 2004).

Wheat production is endangered by *Fusarium species* which cause Fusarium head blight (FHB). Fusarium head blight (FHB) is one of the most devastating diseases of small grain cereals. The dominant fungal agent associated with this disease on wheat is *Fusarium graminearum* (Schwabe), the anamorph of *Gibberella zeae* (Schwabe) Petch (Kikot et al. 2011). During the flowering period when the weather conditions are favorable Fusarium infection will start in the middle of the wheat spikelet and expand within the whole head, leading to bleached spikes and lightweight shriveled kernels (Kelly et al. 2015). This disease not only causes grain yield losses, but also decreases wheat quality and causes the presence of mycotoxins in the grains which are harmful to human and animal health (McMullen et al. 2012; Gärtner et al. 2008).

Crop losses due to FHB represent a significant problem worldwide (Mesterházy et al. 2020). FHB reduces yield and quality of grains, as it is manifested in their weight loss, carbohydrate and protein composition changes and the presence of fungal toxins (Magliano and Kikot 2013). It can destroy starch granules, storage proteins, and grain cell wall and subsequently affect the quality of wheat flour (Dexter et al. 1997). Nightingale et al. (1999) showed that the consistency and resistance to extension of dough was decreased

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when *Fusarium* damaged grains were included in the flour constituents. This resulted in substantial reductions in loaf volume and was attributed to the presence of fungal proteases. Fungal proteases have been shown to lead to weak dough properties and unsatisfactory bread quality (Wang et al. 2005). Additionally, *Fusarium* infection reduces gluten strength in wheat due to lower proportions of glutenin (Dexter et al. 1997). Consequently, FHB infection results in the reduction of end use quality (Dexter and Nowicki 2003). The most important method for FHB control and the reduction of mycotoxin concentration is the use of FHB resistant wheat varieties, appropriate cultural practices, fungicides, biological control and crop rotation (Mesterházy et al. 2015).

Previous studies reported the effect of fertilization (Horváth 2015; Kismányoky and Ragasits 2005; Pepó 2007; Salgó and Gergely 2012), storage time (Móré et al. 2014) and transgenic plant (Rakszegi et al. 2005) on wheat quality. Research on the impact of *Fusarium* infestation on wheat quality is scarce (Spanic et al. 2021). Hence, the aim of this research is to study the effect of *Fusarium* infection on wheat quality parameters: falling number, protein and gluten content, test weight, thousand kernel weight and Zeleny sedimentation index.

Materials and methods

The experiment was conducted during two growing seasons 2020 and 2021 at the experimental field and laboratories of the Hungarian University of Agriculture and Life Sciences (MATE), Crop Production Institute, Gödöllő, Hungary. The experimental site is in a hilly area with a close to average climatic zone of the country (47° 35' 40.8" N 19° 22' 08.4" E, 210 m above sea level). The soil type of the experimental field is brown forest soil (Chromic Luvisol). Prior to sowing, the field was cleared, ploughed, rotor-tilled and the seedbed was prepared. The plots were sown and harvested with plot machines. The wheat variety used in this experiment was Mv Kolompos. The plot area was 75 m² divided in 15 sampling areas of 5 m² each. At the end of each growing season, a wheat kernel sample was taken from each sampling area to measure *Fusarium* infection, protein content, gluten content, test weight, thousand kernel weight, falling number and Zeleny sedimentation index. *Fusarium* infection percentage was calculated by counting the number of colonies that formed on wheat kernels disinfected with a solution of PCNB and chloramphenicol (100 kernels from each sample) incubated for 7 days under laboratory conditions on Nash and Snider *Fusarium* selective medium (Distilled water 1 l, Peptone 15 g, KH₂PO₄ 1 g, MgSO₄·7H₂O 0.5 g, Agar 20 g, PCNB 1 g, Chloramphenicol 100 ppm). Protein content, gluten content and Zeleny sedimentation index were measured by Mininfra Scan-T Plus 2.02 version.

Falling number was measured by ICC method No. 107/1 1995. The OS 1 type equipment by the ISO 7971-3:2019 standard was used to measure test weight. Thousand kernel weight and test weight were measured with the KERN EMS and the Sartorius MA-30 precision scales. IBM SPSS V.21 software was used for the statistical evaluation of the results, the linear regression module at 5% significance level was performed to determine the effect of *Fusarium* infection on wheat quality parameters, and the analysis of variance (ANOVA) module at 5% significance level was performed to determine the effect of the year on *Fusarium* infection and wheat quality parameters.

Results

Fusarium infection in 2021 (94%) is higher than in 2020 (48.4%); this difference is statistically significant [$F(1, 28) = 62.869$, $P = 0.000$] (Table 1).

Simple linear regression is used to test if *Fusarium* infection in 2020 and 2021 growing seasons significantly predicts the following wheat quality parameters: protein content, test weight, thousand kernel weight, falling number, gluten content, and Zeleny sedimentation index.

Protein content in 2021 (14.49%) is lower than in 2020 (15.25%); this difference is statistically significant [$F(1, 28) = 10.559$, $P = 0.003$] (Table 1). The fitted regression model between *Fusarium* infection and protein content is $y = -0.011x + 15.667$. The overall regression is statistically significant [$R^2 = 0.182$, $F(1, 28) = 6.218$, $P = 0.019$]. *Fusarium* infection has a moderate negative effect on protein content in wheat ($R = -0.426$). The increase in *Fusarium* infection leads to a decrease in protein content (Fig. 1, Table 2).

Test weight in 2021 (79.44 kg/hl) is lower than in 2020 (81.15 kg/hl); this difference is statistically significant [$F(1, 28) = 71.975$, $P = 0.000$] (Table 1). The fitted regression model between *Fusarium* infection and test weight is $y = -0.028x + 82.304$. The overall regression is statistically significant [$R^2 = 0.592$, $F(1, 28) = 40.701$, $P = 0.000$]. *Fusarium* infection has a strong negative effect on test weight in wheat ($R = -0.770$). The increase in *Fusarium* infection leads to a decrease in test weight (Fig. 2, Table 2).

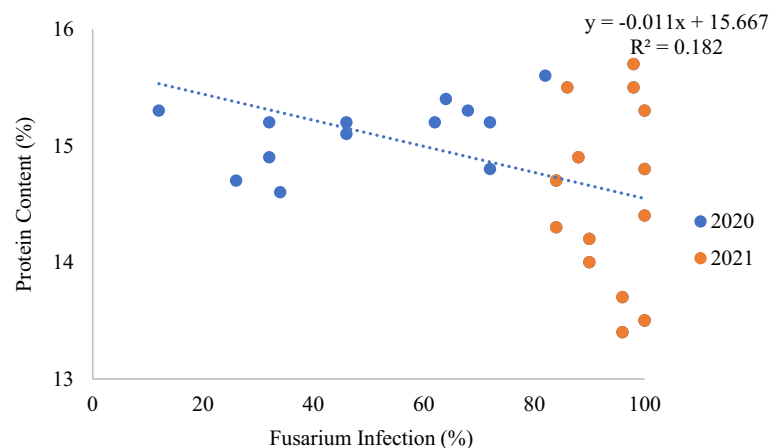
Thousand kernel weight in 2021 (38.68 g) is lower than in 2020 (42.48 g); this difference is statistically significant [$F(1, 28) = 26.306$, $P = 0.000$] (Table 1). The fitted regression model between *Fusarium* infection and thousand kernel weight is $y = -0.051x + 44.230$. The overall regression is statistically significant [$R^2 = 0.266$, $F(1, 28) = 10.155$, $P = 0.004$]. *Fusarium* infection has a moderate negative effect on thousand kernel weight in wheat ($R = -0.516$). The increase in *Fusarium* infection leads to a decrease in thousand kernel weight (Fig. 3, Table 2).

Table 1 Descriptive statistics and ANOVA for the effect of the year on Fusarium infection and wheat quality parameters

Descriptive statistics	Mean	SD	SE	Minimum	Maximum
Fusarium infection					
2020	48.40	21.37	5.52	12	82
2021	94.00	6.28	1.62	84	100
Total	71.20	27.88	5.09	12	100
Protein content					
2020	15.25	0.44	0.11	14.60	16.10
2021	14.49	0.78	0.20	13.40	15.70
Total	14.87	0.73	0.13	13.40	16.10
Test weight					
2020	81.15	0.54	0.14	80.10	81.80
2021	79.44	0.56	0.15	78.35	80.15
Total	80.29	1.02	0.19	78.35	81.80
Thousand kernel weight					
2020	42.48	2.52	0.65	38	46.63
2021	38.68	1.35	0.35	36.35	40.55
Total	40.58	2.77	0.51	36.35	46.63
Falling number					
2020	544.93	60.10	15.52	456	690
2021	358.87	39.08	10.09	298	420
Total	451.90	106.93	19.52	298	690
Gluten content					
2020	31.25	1.33	0.34	29.50	34.20
2021	29.07	2.63	0.68	26.20	33.90
Total	30.16	2.33	0.42	26.20	34.20
Zeleny Sedimentation Index					
2020	63.09	8.15	2.10	53.20	77.70
2021	42.37	5.37	1.39	33.10	50.40
Total	52.73	12.53	2.29	33.10	77.70
ANOVA	Sum of squares	<i>df</i>	Mean square	<i>F</i>	Sig
Fusarium infection					
Between groups	15,595.200	1	15,595.200	62.869	0.000
Within groups	6945.600	28	248.057		
Total	22,540.800	29			
Protein content					
Between groups	4.256	1	4.256	10.559	0.003
Within groups	11.287	28	0.403		
Total	15.543	29			
Test weight					
Between groups	21.845	1	21.845	71.975	0.000
Within groups	8.498	28	0.304		
Total	30.344	29			
Thousand kernel weight					
Between Groups	107.844	1	107.844	26.306	0.000
Within groups	114.790	28	4.100		
Total	222.634	29			
Falling number					
Between groups	259,656.033	1	259,656.033	101.038	0.000
Within groups	71,956.667	28	2569.881		
Total	331,612.700	29			

Table 1 (continued)

ANOVA	Sum of squares	df	Mean square	F	Sig
Gluten content					
Between groups	35.643	1	35.643	8.235	0.008
Within groups	121.187	28	4.328		
Total	156.830	29			
Zeleny Sedimentation Index					
Between groups	3221.960	1	3221.960	67.705	0.000
Within groups	1332.463	28	47.588		
Total	4554.423	29			

Fig. 1 Regression slope intercept between Fusarium infection (%) and protein content (%) in 2020 and 2021 growing seasons

Falling number in 2021 (358.87 s) is lower than in 2020 (544.93 s); this difference is statistically significant [$F(1, 28) = 101.038$, $P = 0.000$] (Table 1). The fitted regression model between Fusarium infection and falling number is $y = -2.908x + 658.924$. The overall regression is statistically significant [$R^2 = 0.575$, $F(1, 28) = 37.831$, $P = 0.000$]. Fusarium infection has a strong negative effect on falling number in wheat ($R = -0.758$). The increase in Fusarium infection leads to a decrease in falling number (Fig. 4, Table 2).

Gluten content in 2021 (29.07%) is lower than in 2020 (31.25%); this difference is statistically significant [$F(1, 28) = 8.235$, $P = 0.008$] (Table 1). The fitted regression model between Fusarium infection and gluten content is $y = -0.036x + 32.727$. The overall regression is statistically significant [$R^2 = 0.186$, $F(1, 28) = 6.414$, $P = 0.017$]. Fusarium infection has a moderate negative effect on gluten content in wheat ($R = -0.432$). The increase in Fusarium infection leads to a decrease in gluten content (Fig. 5, Table 2).

Zeleny Sedimentation Index in 2021 (42.37 ml) is lower than in 2020 (63.09 ml); this difference is statistically significant [$F(1, 28) = 67.705$, $P = 0.000$] (Table 1). The fitted regression model between Fusarium infection and Zeleny sedimentation index is $y = -0.305x + 74.443$. The overall regression was statistically significant [$R^2 = 0.460$, $F(1,$

$28) = 23.879$, $P = 0.000$]. Fusarium infection has a strong negative effect on Zeleny sedimentation index in wheat ($R = -0.678$). The increase in Fusarium infection leads to a decrease in Zeleny sedimentation index (Fig. 6, Table 2).

Discussion

The present study was carried out to determine the effect of Fusarium infection on wheat quality in 2020 and 2021 growing seasons. The different climatic conditions that prevailed during 2020 and 2021 growing seasons could be the reason for the increase in Fusarium infection which leads to the decrease in wheat quality. According to El Chami et al. (2022), climatic factors play a key role in determining fungal occurrence. Thus, the activity of the fungi and their level of colonization are much determined by environmental conditions. In our study the increase in Fusarium infection showed a negative impact on wheat quality. Antes et al. (2001) and Prange et al. (2005) found that a strong Fusarium infection did not significantly influence wheat quality parameters. On the contrary, Gärtner et al. (2008) and Seitz et al. (1986) observed in their studies that Fusarium infection has negative effects on wheat quality parameters. The results obtained showed that Fusarium infection decreases protein

Table 2 Model summary, ANOVA and coefficients for the effect of Fusarium infection on wheat quality parameters

Model summary	<i>R</i>	<i>R</i> ²	Adjusted <i>R</i> ²	Std. error of the estimate	
Protein content	0.426	0.182	0.152	0.674	
Test weight	0.770	0.592	0.578	0.665	
Thousand kernel weight	0.516	0.266	0.240	2.416	
Falling number	0.758	0.575	0.559	70.974	
Gluten content	0.432	0.186	0.157	2.135	
Zeleny Sedimentation Index	0.678	0.460	0.441	9.370	
ANOVA	Sum of squares	<i>df</i>	Mean square	<i>F</i>	Sig
Protein content					
Regression	2.824	1	2.824	6.218	0.019
Residual	12.719	28	0.454		
Total	15.543	29			
Test weight					
Regression	17.977	1	17.977	40.701	0.000
Residual	12.367	28	0.442		
Total	30.344	29			
Thousand kernel weight					
Regression	59.254	1	59.254	10.155	0.004
Residual	163.380	28	5.835		
Total	222.634	29			
Falling number					
Regression	190,567.506	1	190,567.506	37.831	0.000
Residual	141,045.194	28	5037.328		
Total	331,612.700	29			
Gluten content					
Regression	29.228	1	29.228	6.414	0.017
Residual	127.602	28	4.557		
Total	156.830	29			
Zeleny Sedimentation Index					
Regression	2096.331	1	2096.331	23.879	0.000
Residual	2458.092	28	87.789		
Total	4554.423	29			
Coefficients	Unstandardized coefficients		Standardized coefficients	<i>t</i>	Sig
	B	SE	Beta		
Protein content					
Fusarium	− 0.011	0.004	− 0.426	− 2.494	0.019
(Constant)	15.667	0.342		45.745	0.000
Test weight					
Fusarium	− 0.028	0.004	− 0.770	− 6.380	0.000
(Constant)	82.304	0.338		243.703	0.000
Thousand kernel weight					
Fusarium	− 0.051	0.016	− 0.516	− 3.187	0.004
(Constant)	44.230	1.228		36.032	0.000
Falling number					
Fusarium	− 2.908	0.473	− 0.758	− 6.151	0.000
(Constant)	658.924	36.067		18.270	0.000
Gluten content					
Fusarium	− 0.036	0.014	− 0.432	− 2.533	0.017

Table 2 (continued)

Coefficients	Unstandardized coefficients		Standardized coefficients Beta	<i>t</i>	Sig
	B	SE			
(Constant)	32.727	1.085		30.168	0.000
Zeleny Sedimentation Index					
Fusarium	− 0.305	0.062	− 0.678	− 4.887	0.000
(Constant)	74.443	4.761		15.635	0.000

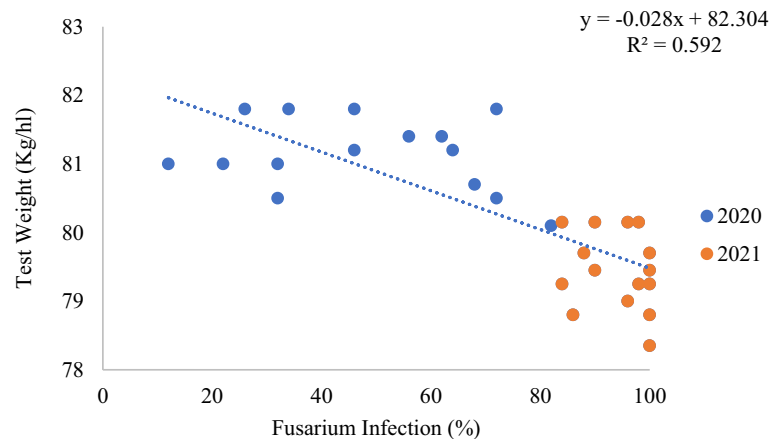
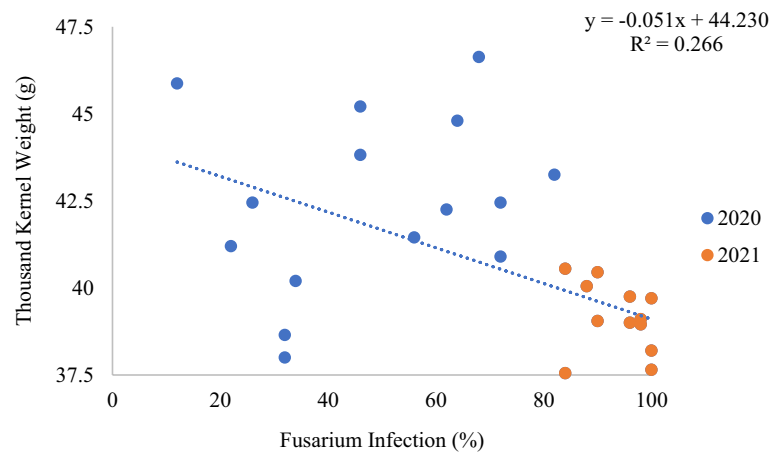
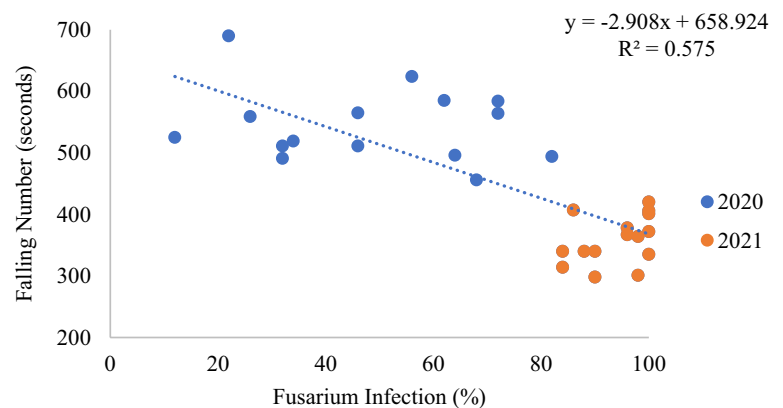
Fig. 2 Regression slope intercept between Fusarium infection (%) and test weight (Kg/hl) in 2020 and 2021 growing seasons**Fig. 3** Regression slope intercept between Fusarium infection (%) and thousand kernel weight (g) in 2020 and 2021 growing seasons**Fig. 4** Regression slope intercept between Fusarium infection (%) and falling number (seconds) in 2020 and 2021 growing seasons

Fig. 5 Regression slope intercept between Fusarium infection (%) and gluten content (%) in 2020 and 2021 growing seasons

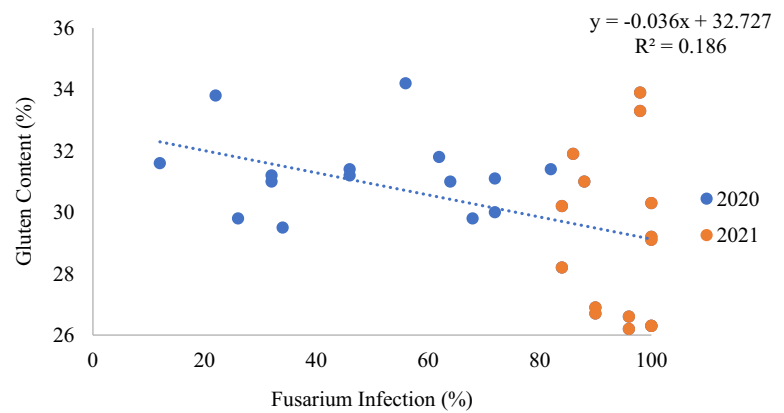
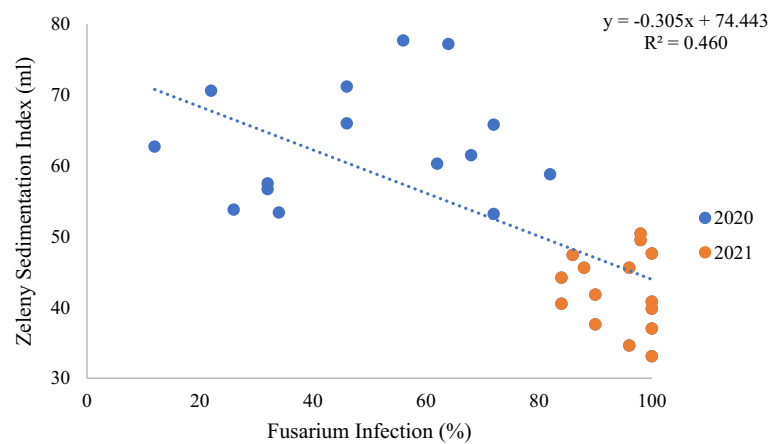


Fig. 6 Regression slope intercept between Fusarium infection (%) and Zeleny sedimentation index (ml) in 2020 and 2021 growing seasons



and gluten content. Dexter et al. (1997) and Gärtner et al. (2008) observed in their research a slight decrease in protein and gluten content in wheat kernels after Fusarium infection. Wang et al. (2005) concluded that protein and gluten content in the wheat grain were not affected by Fusarium infection. However, Boyacıoğlu and Hettiarachchy (1995) concluded that protein and gluten content in wheat kernels increased following their contamination with *Fusarium species*. The results obtained revealed that Zeleny sedimentation index and falling number were significantly reduced by Fusarium infection. Papoušková et al. (2011) observed that Zeleny sedimentation index and falling number showed distinctively decreased values in the infected samples. Meyer et al. (1986) and Gärtner et al. (2008) observed general reduction of Zeleny sedimentation index in wheat grains after Fusarium infection. According to Hareland (2003), Fusarium infection increases the degradation of starch in wheat kernels due to the presence of enzymes such as α -amylase which in turn decreases the quality of wheat flour and results in lower falling number values. The results obtained indicated that test weight and thousand kernel weight were significantly decreased by Fusarium infection. Test weight is primarily a function of the size of the grains. The fact that Fusarium infection affects test weight has been well documented

(McMullen et al. 2012; Wong et al. 1995). Spanic et al. (2017) findings suggest that Fusarium infection has a negative effect on test weight. Dexter et al. (1996), Wang et al. (2005) and Dvojkovic et al. (2007) found that Fusarium infection resulted in a decrease of thousand kernel weight. Fusarium infected kernels are damaged, shriveled, shrunken and light weight showing a tendency towards a decrease in the endosperm to bran ratio due to fungal carbohydrate consumption. Results from the mentioned studies indicate that Fusarium infection may alter and lead to the deterioration of wheat quality parameters.

Conclusion

The results indicate that Fusarium infection in 2021 (94%) is higher than in 2020 (48.4%). The increase in Fusarium infection reduces wheat quality. Hence, it negatively affects protein content, test weight, thousand kernel weight, falling number, gluten content and Zeleny sedimentation index. The higher the Fusarium infection the lower the value of wheat quality parameters.

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Declarations

Conflict of interest The authors declare that there is no conflict of interest.

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References

- Antes S, Birzele B, Prange A, Krämer J, Meier A, Dehne HW, Köhler P (2001) Rheological and breadmaking properties of wheat samples infected with *Fusarium* spp. *Mycotoxin Res* 17(Suppl 1):76–80. <https://doi.org/10.1007/BF03036717>
- Boyacıoğlu D, Hettiarachchy NS (1995) Changes in some biochemical components of wheat grain that was infected with *Fusarium graminearum*. *J Cereal Sci* 21:57–62. [https://doi.org/10.1016/S0733-5210\(95\)80008-5](https://doi.org/10.1016/S0733-5210(95)80008-5)
- Horváth CS (2015) Impact of nitrogen supply on the performance of quality parameters and protein compounds of five winter wheat (*Triticum aestivum* L.) varieties. Doctoral (PhD) thesis, SZIU. Gödöllő
- Dexter JE, Nowicki TW (2003) Safety assurance and quality assurance issues associated with fusarium head blight in wheat. In: Leonard KJ, Bushnell WR (eds) *Fusarium head blight of wheat and barley*. APS Press, St. Paul, pp 420–460
- Dexter JE, Clear RM, Preston KR (1996) Fusarium head blight: effect on milling and baking of some Canadian wheats. *Cereal Chem* 73:695–701
- Dexter JE, Marchylo BA, Clear RM, Clarke JM (1997) Effect of fusarium head blight on semolina milling and pasta-making quality of durum wheat. *Cereal Chem* 74:519–525. <https://doi.org/10.1094/CCHEM.1997.74.5.519>
- Dvojkovic K, Drezner G, Horvat D, Novoselovic D, Spanic V (2007) Fusarium head blight influence on agronomic and quality traits of winter wheat cultivars. *Cereal Res Commun* 35:365–368. <https://doi.org/10.1556/CRC.35.2007.2.50>
- El Chami E, El Chami J, Tarnawa Á, Kassai KM, Kende Z, Jolánkai M (2022) Influence of growing season, nitrogen fertilisation and wheat variety on Fusarium infection and mycotoxin production in wheat kernel. *Acta Aliment* 51:282–289. <https://doi.org/10.1556/066.2022.00036>
- Gärtner BH, Munich M, Kleijer G, Mascher F (2008) Characterisation of kernel resistance against Fusarium infection in spring wheat by baking quality and mycotoxin assessments. *Eur J Plant Pathol* 120:61–68. <https://doi.org/10.1007/S10658-007-9198-5>
- Hareland GA (2003) Effects of pearling on falling number and α -amylase activity of preharvest sprouted spring wheat. *Cereal Chem* 80:232–237. <https://doi.org/10.1094/CCHEM.2003.80.2.232>
- Hung PV (2016) Phenolic compounds of cereals and their antioxidant capacity. *Crit Rev Food Sci Nutr* 56:25–35. <https://doi.org/10.1080/10408398.2012.708909>
- ICC(1995) Determination of the Falling Number according to Hagberg - as a measure of the degree of alpha-amylase activity in grain and flour. Method No. 107/1
- ISO (2019) Cereals—determination of bulk density, called mass per hectoliter. ISO 7971-3:2019
- Jones JM, Peña RJ, Korczak R, Braun HJ (2015) Carbohydrates, grains, and wheat in nutrition and health: an overview part I. Role of carbohydrates in health. *Cereal Foods World* 60:224–233. <https://doi.org/10.1094/CFW-60-5-0224>
- Kelly AC, Clear RM, O'Donnell K, McCormick S, Turkington TK, Tekauz A, Gilbert J, Kistler HC, Busman M, Ward TJ (2015) Diversity of Fusarium head blight populations and trichothecene toxin types reveals regional differences in pathogen composition and temporal dynamics. *Fungal Genet Biol* 82:22–31. <https://doi.org/10.1016/J.FGB.2015.05.016>
- Khan H (2019) Genetic improvement for end-use quality in wheat. *Qual Breed Field Crops*. https://doi.org/10.1007/978-3-030-04609-5_12
- Kikot GE, Moschini R, Consolo VF, Rojo R, Salerno G, Hours RA, Gasoni L, Arambarri AM, Alconada TM (2011) Occurrence of different species of fusarium from wheat in relation to disease levels predicted by a weather-based model in Argentina pampas region. *Mycopathologia* 171:139–149. <https://doi.org/10.1007/S11046-010-9335-0>
- Kismányoky T, Ragasits I (2005) Effects of organic and inorganic fertilization on wheat quality. *Acta Agron Hung* 51:47–52. <https://doi.org/10.1556/AAGR.51.2003.1.6>
- Magliano TMA, Kikot GE (2013) Fungal infection and disease progression. *Fusarium* spp. enzymes associated with pathogenesis and loss of commercial value of wheat grains. *Fusarium Head Blight Latin Am*. https://doi.org/10.1007/978-94-007-7091-1_7
- McMullen M, Bergstrom G, Wolf ED, Dill-Macky R, Hershman D, Shaner G, Sanford DV (2012) A unified effort to fight an enemy of wheat and barley: fusarium head blight. *Plant Dis*. <https://doi.org/10.1094/PDIS-03-12-0291-FE>
- Mesterházy A, Lehoczi-Krsjak S, Varga M, Szabó-Hevéri Á, Tóth B, Lemmens M (2015) Breeding for FHB resistance via fusarium damaged kernels and deoxynivalenol accumulation as well as inoculation methods in winter wheat. *Agric Sci* 06:970–1002. <https://doi.org/10.4236/AS.2015.69094>
- Mesterházy A, Oláh J, Popp J (2020) Losses in the grain supply chain: causes and solutions. *Sustainability*. <https://doi.org/10.3390/SU12062342>
- Meyer D, Weipert D, Mielke H (1986) Beeinflussung der Qualität von Weizen durch den Befall mit *Fusarium culmorum*. *Getreide Mehl Und Brot* 40:35–39
- Móré M, Diósi G, Győri Z, Sipos P (2014) Influence of storage time on the gluten properties of winter wheat. *J Process Energy Agric* 18:197–199
- Nightingale MJ, Marchylo BA, Clear RM, Dexter JE, Preston KR (1999) Fusarium head blight: effect of fungal proteases on wheat storage proteins. *Cereal Chem* 76:150–158. <https://doi.org/10.1094/CCHEM.1999.76.1.150>

- Papoušková L, Capouchová I, Kostelanská M, Škeříkova A, Prokinová E, Hajšlová J, Salava J, Faměra O (2011) Changes in baking quality of winter wheat with different intensity of *Fusarium* spp. contamination detected by means of new rheological system. Czech J Food Sci 29:420–429. <https://doi.org/10.17221/426/2010-CJFS>
- Pepó P (2007) The role of fertilization and genotype in sustainable winter wheat (*Triticum aestivum* L.) production. Cereal Res Commun 35:917–920. <https://doi.org/10.1556/CRC.35.2007.2.188>
- Prange A, Birzele B, Krämer J, Meier A, Modrow H, Köhler P (2005) Fusarium-inoculated wheat: deoxynivalenol contents and baking quality in relation to infection time. Food Control 16:739–745. <https://doi.org/10.1016/J.FOODCONT.2004.06.013>
- Rakszegi M, Békés F, Láng L, Tamás L, Shewry PR, Bedő Z (2005) Technological quality of transgenic wheat expressing an increased amount of a HMW glutenin subunit. J Cereal Sci 42:15–23. <https://doi.org/10.1016/J.JCS.2005.02.006>
- Salgó A, Gergely S (2012) Analysis of wheat grain development using NIR spectroscopy. J Cereal Sci 56:31–38. <https://doi.org/10.1016/J.JCS.2012.04.011>
- Seitz LM, Eustace WD, Nohr HE, Shorgen MD, Yamazaki WT (1986) Cleaning, milling and baking tests with hard red winter wheat containing deoxynivalenol. Cereal Chem 63:146–150
- Shewry PR (2004) Protein synthesis and deposition. Encycl Grain Sci. <https://doi.org/10.1016/B0-12-765490-9/00131-2>
- Spanic V, Vuletic MV, Drezner G, Zdunic Z, Horvat H (2017) Performance indices in wheat chlorophyll a fluorescence and protein quality influenced by FHB. Pathogens 6:59. <https://doi.org/10.3390/PATHOGENS6040059>
- Spanic V, DvojkoVIC K, Babic J, Drezner G, Zdunic Z (2021) Fusarium head blight infestation in relation to winter wheat end-use quality—a three-year study. Agronomy. <https://doi.org/10.3390/AGRONOMY11081648>
- Wang JH, Wieser H, Pawelzik E, Weinert J, Keutgen AJ, Wolf GA (2005) Impact of the fungal protease produced by *Fusarium culmorum* on the protein quality and breadmaking properties of winter wheat. Eur Food Res Technol 220:552–559
- Wong LSL, Abramson D, Tekauz A, Leisle D, McKenzie RH (1995) Pathogenicity and mycotoxin production of *Fusarium* species causing head blight in wheat cultivars varying in resistance'. Can J Plant Sci 75:261–267