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Fusarium head blight in winter wheat: development peculiarities and protective strategies

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Abstract. *Fusarium* head blight (FHB, caused by the fungal plant pathogen *Fusarium graminearum* Schwabe) is a widespread fungal disease in the Republic of Armenia, affecting various cereal crops, including wheat, leading to a decrease in productivity and grain quality. However, comprehensive research aimed at selecting proper fungicides and determining the optimal application timing has not been conducted before.
FHB can undergo epidemic development during years characterized by favorable weather conditions. Conversely, during periods of adverse weather conditions, the severity and incidence of FHB tend to decrease notably. Abundant rainfall and mild temperatures render plants more susceptible, facilitating the spread of infection not only during the flowering of winter wheat but also at the waxy ripening stage, thereby increasing the risk of an FHB epidemic.
The experiments were carried out during the 2022 and 2023 growing seasons under rain-fed conditions, with the primary focus on treating winter wheat with triazole group fungicides.
During years with adverse weather conditions for FHB development, a single application of Falcon (0.5 L ha^{-1}) or Prosaro (1.0 L ha^{-1}) at Feekes 10.5.1 proved to be an effective strategy for managing FHB, particularly when integrated with cultural practices. These treatments provided a biological efficacy of 80.6% to 83.3% at Feeks 11.2, and from 76.6% to 79.4% at harvest, respectively, increasing wheat yield by 37.62% to 42.9%.
In the case of epidemic development of FHB during years with more favorable weather conditions, a double fungicide treatment (Falcon or at Feekes 10.3 and Prosaro at Feekes 10.5.1) was the most effective option, showing high biological efficacy (97.4% at Feeks 11.2 and 90.3% at harvest) against FHB of winter wheat, increasing wheat yield by 40.1%.

Key words: *Fusarium* head blight, winter wheat, triazole fungicides, biological efficacy.

INTRODUCTION

Cereal crops play indispensable roles in global food systems, serving as critical components in nutrition, economics, and food security worldwide. They are cultivated in larger quantities and contribute more food energy worldwide than any other crop type, making them essential staple food crops (Sarwar et al., 2013).

The production of grain is of strategic importance for ensuring the food and national security of the Republic of Armenia. Out of 227.2 hectares of cultivated land in the RA territory, 124,96 hectares, or 55%, are occupied by grain and leguminous crops. In 2021, the average yield of wheat (both autumn and spring varieties) was 1.68 metric tons per hectare (t ha^{-1}), and it was lower than the yield recorded in 2017 (which was 2.18 t ha^{-1}) by 0.5 tons or 22.9% (Statistical Yearbook of Armenia, 2022).

Climate change, violations of cultivation technology (such as improper selection of seeds, monoculture of cereal crops, and inadequate control of harmful organisms), among other factors, significantly contribute to low yield levels. Herbicides are the main pesticides that are used during the cultivation of grain crops in RA, and in the conditions of monoculture, an intensive development of diseases and pests is observed, their harmfulness continues to increase over time. Climate change, along with violations of cultivation technology such as improper seed selection, monoculture of cereal crops, and insufficient control of harmful organisms, are significant contributors to low yield levels. In the Republic of Armenia, herbicides serve as the primary pesticides used during the cultivation of grain crops. Under monoculture conditions, there is a noticeable intensification of diseases and pests, with their harmful impact progressively worsening over time.

Considering the nutritional value and economic importance of cereal crops for food security, as well as the impact of global climate change on grain yield quality and quantity, especially in arid and semiarid regions, research in recent years by numerous authors from different countries has aimed at increasing the productivity of cereal crops and grain quality using various technologies and agricultural practices. Research areas encompass various aspects, including:

– Implementation of soil tillage practices and weed management strategies (Bani Khalaf et al., 2021); exploration of short-term tillage and no-tillage methods in conjunction with chemical treatments (Guedioura et al., 2023); evaluation of different cultivation technologies (Zargar et al., 2018);

– Optimization of plant nutrition systems (Radchenko et al., 2021), particularly focusing on nitrogen fertilizer rates in winter wheat (Litke et al., 2019); investigation into the impact of bio-humus on soil fertility and spring wheat productivity (Muhamedyarova et al., 2020); study of the effects of environmentally friendly fertilizer (acceptable in green agriculture) on cereal crops (Martirosyan et al., 2023);

– Development of farming practices aimed at enhancing the productivity of winter wheat through the utilization of pesticides from different groups (Kuznetsov et al., 2020); adoption of new technologies for fungicide treatment schemes (both chemical and biological); protection of cereal crops from root rot development using Bacillus subtilis (Kolesnikov et al., 2021); combatting leaf rust and blotches (Švarta et al., 2022), *Fusarium* head blight (González-Domínguez et al., 2021), etc.

The importance of *Fusarium* head blight on wheat cannot be overstated (Shude et al., 2020). It is a severe fungal disease that profoundly impacts cereal crops worldwide, representing a substantial threat to both agricultural productivity and food safety. FHB not only reduces crop yield and quality but also poses health risks due to the production of mycotoxins. These mycotoxins can contaminate grain, posing harm to humans and animals upon ingestion (Mudge et al., 2006; Malekinejad et al., 2007; Duffeck et al., 2020; Mesterhazy, 2020; Wu et al., 2023; Miedaner et al., 2024).

Fusarium head blight (FHB) epidemics have become an increasing problem over the last decades (Alisaac et al., 2019; Ma et al., 2022), likely due to the increased adoption of conservation tillage practices, the use of susceptible wheat varieties, and climate variability (Haile et al., 2019; Spanic et al., 2019; Dong et al., 2020). Moreover, yield losses due to the disease can reach up to 80% of the crop (Alisaac & Mahlein, 2023).

Fungicides have historically served as the primary method for managing FHB (Siranidou & Buchenauer, 2001; Haidukowski et al., 2005; Lehoczki-Krsjak et al., 2010; Shude et al., 2020). However, their effectiveness is often hampered by the development of fungicide resistance (Anderson et al., 2020; Chen et al., 2021; Zhao et al., 2022) and environmental concerns.

Crop rotation and tillage practices have also been implemented as strategies to mitigate FHB by reducing the levels of inoculum in the soil (Schaafsma et al., 2005; McMullen et al., 2012; Wegulo et al., 2015; Fernando et al., 2021). Concurrently, breeding efforts aimed at developing FHB-resistant crop varieties (Mesterházy et al., 1999; Buerstmayr et al., 2019; Fernando et al., 2021) represent a long-term approach to disease management.

Biological control methods, such as the use of antagonistic microbes, beneficial fungi (Khan et al., 2001; Chen et al., 2018; Drakopoulos et al., 2019; Drakopoulos et al., 2020), and essential oils derived from plant sources, have been explored (Kumar et al., 2016; Ferreira et al., 2018) as potential alternatives to chemical fungicides for suppressing *Fusarium* spp. However, the practical implementation of these methods has faced challenges due to practical constraints. The efficacy of biocontrol agents is contingent upon various factors, including weather conditions, crop stage, formulation, and the specific type of agent (Elnahal et al., 2022).

Recent literature underscores the importance of integrating diverse management practices, including cultural, chemical, and biological approaches, to effectively combat FHB (Shah et al., 2018; Chen et al., 2022; Alisaac & Mahlein, 2023).

Fusarium head blight is a common fungal disease in the Republic of Armenia (RA); however, there has been no comprehensive research conducted previously to select appropriate fungicides and determine the optimal timing for their application. This study aims to investigate the development peculiarities of FHB and develop strategies to reduce disease development while enhancing the productivity of winter wheat under rain-fed agricultural conditions. This research represents a novel approach, focusing on the assessment of triazole-group fungicides and identifying the optimal application timing in combating FHB.

MATERIAL AND METHODS

Experimental site and meteorological data recorded

The research was conducted during the 2022 and 2023 growing seasons in rain-fed cultivation conditions in the Spitak community of Lori marz in the Republic of Armenia, situated at coordinates 40°49'55.96"N, 44°16'2.32"E. The climate in Spitak is characterized by winters with a permanent snow cover and warm, relatively humid summers. The average air temperature ranges from -8 °C in winter to +18 °C in summer, with a mean temperature of +5 °C. August marks the hottest, while January is the coldest month. May typically receives the highest amount of precipitation, averaging 89.4 mm, with annual precipitation totaling 398.1 mm per year.

The multi-annual monthly agroclimatic data for the Spitak region were sourced from Arazyan & Shekoyan, 2006. Meteorological data for both the 2022 and 2023 vegetation periods were provided by the 'Hydrometeorology and Monitoring Center' SNCO of the Ministry of Environment of RA.

Experimental design

The experiments were conducted during the 2022 and 2023 growing seasons in rain–fed cultivation conditions, with the primary focus on applying fungicides to winter wheat. Both single and double preventive applications of fungicides were considered as the main factors in the study.

The winter wheat cultivar Bezostaya 1, widely cultivated in Armenia, was planted on September 20, 2021, and September 15, 2022. Comprehensive agricultural practices were implemented throughout the entire experimental field, including tillage, residue, and weed management, to mitigate inoculum levels. Additionally, early sowing dates were chosen to avoid the peak of *Fusarium* spore production, while careful attention was paid to avoiding excessive nitrogen fertilization to enhance crop health and reduce susceptibility to disease.

The experimental field for testing fungicides was divided into plots, each measuring 10 m^2, with three replicates for each treatment option. Additionally, 40 cm -wide wheat stripe areas with no treatments were left between plots to minimize potential interference or contamination between treatments.

Fusarium graminearum, the causative species of *Fusarium* head blight (FHB), was isolated from sampled infected kernels using PDA media.

Assessment of disease development

Severity and incidence of FHB in winter wheat, disease development degree (DDD, which is a metric similar to the Disease Severity Index (DSI)), and biological efficacy of applied pesticides were determined using methods accepted in plant pathology (Dementyeva, 1985; Avagyan, 2006; Shin et al., 2014; Arcibal et al., 2016).

One hundred spikes from various locations within the plot were assessed to measure *Fusarium* head blight (FHB) severity (in scores) and disease incidence (%).

FHB severity was evaluated as the percentage of spikelets on the spikes displaying visually detectable disease symptoms at the wheat late milk growth stage Feekes 11.2 (Large, 1954), as well as at harvest (Feekes 11.4). This assessment was conducted using a 5-point severity scale:

- 0-point score severity: absence of FHB infection, indicating a healthy spike.
- 1-point severity score: up to 10% of spikelets of the spike (head) are infected, showing discoloration or covered with perithecia.
- 2-point severity score: 10.1–25% of spikelets of the spike (head) are infected, displaying discoloration or covered with perithecia.
- 3-point severity score: 25.1–50% of spikelets of the spike (head) are infected.
- 4-point severity score: more than 50% of spikelets of the spike (head) are infected.

FHB incidence was calculated using the following formula:

Incidence = (Number of infected spikes/Total number of calculated spikes) × 100%.

The Disease Development Degree (DDD) was calculated using the following formula:

DDD = [∑(disease severity score×number of infected spikes with corresponding severity score)]/[(total number of calculated spikes)×(maximal score (4) in the disease severity score scale)]×100%.

The Biological Efficacy of fungicides was calculated using the following formula:

Be = [(disease development degree in untreated check (control) option-disease development degree in the option with fungicide application)] / [disease development degree in untreated check option]×100% (Dementyeva, 1985).

Additionally, yield was calculated using the metric method, with data collected from three repetitions of each variant (Kuznetsov, 1980).

Statistical assessment of the results

Statistical assessment was conducted using the single-factor or one-way ANOVA test (analysis of variance). The MS Excel package was utilized to compare the average data across the experimental options and to display standard deviation and error bars. The indicator of the least significant difference (*LSD* 0.5) was applied with the lower limit of the permissible level of significance set at $p < 0.05$.

RESULTS AND DISCUSSION

The host plants for *Fusarium* head blight are wheat (*Triticum aestivum* L.), durum wheat (*Triticum durum* L.), barley (*Hordeum vulgare* L.), oats (*Avena sativa* L.), rye (*Secale cereale* L.), corn (*Zea mays* L.), etc. Wheat and barley are among the most frequently infected crops by *Fusarium* head blight.

The causal agents of *Fusarium* head blight are encompassing various species within the *Fusarium* Link genus (Zemánková & Lebeda, 2001). *Fusarium graminearum* Schwabe, with its sexual stage known as *Gibberella zeae* (Schwein.) Petch, stands out as one of the most prevalent and significant species linked to FHB. However, other *Fusarium* species such as *F. culmorum* (W.G.Sm.) Sacc., *F. avenaceum* (Corda ex Fries) Sacc., *F. sporotrichioides* Sherb., and several others can also cause FHB in cereal crops. The negative effect of *Fusarium* spp. is manifested in the yield decrease, as well as in the accumulation of the mycotoxin deoxynivalenol (DON) in the infected grain (Parry et al., 1995; Stack, 2000; Bekele, 2018; Shah et al., 2018).

Fusarium head blight was first identified in England in 1884 (Shah et al., 2018). FHB is now widespread throughout the world (McMullen et al., 2017). The symptoms of the disease can be both visible and hidden-latent. If symptoms are noticeable, grains are deformed and orange spore masses appear on the margin of the glumes of infected spikelets. In the case of latent symptoms, no diagnostic signs of FHB are observed, as noted by Parry et al. (1995), which leads to the synthesis of the DON in the grains (Clement et al., 1998).

The severity of FHB symptoms can vary depending on factors such as environmental conditions, host susceptibility, etc. During our observations in 2022–2023, the most common symptom of FHB was premature bleaching of the entire spike or individual spikelets (Fig. 1, a). Premature bleaching progresses over time on most or all spikelets, eventually causing the entire head to bleach (Avagyan, 2006).

Figure 1. Symptoms of *Fusarium* head blight: bleached spikes during milky ripening stage (a), infected heads during waxy ripening stage (b), perithecia on the spikes (c).

Bleached spikelets are sterile or contain shriveled and lightweight kernels compared to healthy ones. In case of severe infection, the spike becomes completely deformed and wrinkled (Fig. 1, b). During waxy ripening stage, the pathogen forms perithecia on the surface of wheat spikelets (Fig. 1, c). Under favorable wet conditions, perithecia may also appear on the leaves and stem of wheat (Fig. 2). Infected heads ripen prematurely, leading to reduced yield.

Figure 2. Perithecia of *F. graminearum (G. zeae)* on wheat leaves and stem.

Additionally, the pathogen can cause symptoms of crown and root rot, characterized by the rotting and decay of the crown tissue at the soil surface (Fig. 3).

Figure 3. Symptoms of *Fusarium* crown rot: infected (left) and healthy (right) plants.

Our observations during the 2022 and 2023 growing seasons in different regions of RA have revealed outbreaks of massive FHB development, particularly in regions such as Spitak and Aparan, situated at elevations ranging from 1,650 to 1,880 meters above sea level. These regions were characterized by high levels of precipitation, especially during the heading and flowering stages of winter wheat. This pattern persisted during years with substantial precipitation, such as 2023, observed in regions like Ararat, Armavir, and Kotayk, which are situated at elevations ranging from 825 to 1,450 meters above sea level.

F. graminearum overwinters either as perithecia (*G. zeae*) or mycelia in the soil or within host crop residues, which serving as a source of primary infection during the subsequent spring. In spring, under favorable weather conditions (warm and humid), ascospores and/or conidia are released from crop residues. These spores are then disseminated by wind or splashing water, and upon landing on wheat heads, they germinate and infect glumes, flowers, and other parts of the heads (Vaughan et al., 2016; Shah et al., 2018; Teli et al., 2020; Windels, 2000).

An effective strategy to manage *Fusarium* head blight in wheat is the use of fungicides. Some research studies have indicated that the application of strobilurin fungicides can lead to increased DON levels in the harvested grains (Bonfada, et al., 2019; Gaurilèikienë et al., 2005).

Therefore, for the experiments, fungicides from the chemical group of triazoles were selected, including Tilt® (applied at a rate of 0.5 L ha^{-1}), Alto super (0.5 L ha^{-1}), Falcon (0.8 L ha^{-1}), Folicur® (0.5 L ha^{-1}), Prosaro® (1.0 L ha^{-1}).

It is widely recognized that the development of *Fusarium* head blight is strongly influenced by climatic conditions. Wheat becomes susceptible to FHB from the heading stage to the beginning of the waxy ripening stage, with the critical window for head infection occurring during anthesis (Bai et al., 1996; Hooker et al., 2002; Yoshida et al., 2007; Sioua et al., 2014; Brauer et al., 2020). Thus, during the 2022 growing season, pesticides were applied preventively at the wheat growing stage Feekes 10.5.1 (early anthesis). During the 2023 growing season, pesticides were applied preventively mostly at the wheat growing stage Feekes 10.5.1, similar to 2022. However, double sprayings were carried out in two options: the first at Feekes 10.3, when half of the heading process had been completed, and the second at Feekes 10.5.1.

The basis for carrying out double spraying was the data obtained during 2022, which demonstrated that from the milky ripening stage to the waxy ripening stage and harvest of winter wheat, the disease can progress, intensively forming perithecia on the ears, stems and leaves. We have also considered the data on weather conditions of 2022 and 2023 (Table 1), as the severity of FHB in rain–fed agriculture mainly depends on weather conditions.

The average monthly air temperature during April–July months of 2022 was generally higher (10.5–19.7 °C), whereas the total amount of precipitation during some months was lower (10.5–34.8 mm during July and April) or higher (90.3–111.2 mm during June and May), compared to the multi–annual monthly averages (Table 1). The average monthly air temperature during 2023 was generally lower (9.3–18.8 °C) compared to 2022, but it was higher compared to the multi–annual data. Meanwhile, the total amount of precipitation was higher (65.6–107.9 mm) compared to 2022, as well as the multi–annual monthly averages. Under such conditions of high precipitation and moderate temperature, it is necessary to spray not only during the phase of massive maturation and release of the pathogen's ascospores – when plants are at the flowering stage (Feekes 10.5.1), potentially facing massive infection - but also earlier, when half of the heading process is completed (Feekes 10.3). The first application of fungicides at Feekes 10.3 will coincide with the initial stage of maturation and release of the pathogen's ascospores from perithecia, whereas the second one (at Feekes 10.5.1) will align with the phase of massive maturation and release of the ascospores. This approach reduces the amount of inoculum and the likelihood of subsequent infection of the spikes.

Table 1. Total amount of precipitation, average air temperature and relative humidity data for Spitak region, RA

Indicators of climate conditions	Year	Months				
		April	May	June	July	August
Average air temperature, °C	2022	10.5	11.4	17.7	19.7	20.3
	2023	9.3	12.5	16.4	18.8	21.2
Multi-annual temperature, °C	-	6.4	11.6	14.8	18.0	18.0
Total amount of precipitation, mm	2022	34.8	111.2	90.3	10.5	22.6
	2023	65.6	93.01	107.9	84.1	19.5
Multi-annual precipitation, mm	–	56	78	78	50	36
Average relative humidity, %	2022	70	81	85	63	60
	2023	63	66	70	69	66
Multi-annual relative humidity, %	-	66	69	70	68	65

According to the data presented in Table 2, the incidence of FHB in the untreated check (control) option was 22.3% and 26.8% at Feekes 11.2 and Feekes 11.4, respectively, in 2022. The average disease severity scores were 1.3 and 1.6, and the degree of disease development being 7.2% and 10.7%, respectively. The high amount of precipitation (90.3 mm) in June 2022 contributed to the development of FHB.

Table 2. Impact of fungicide treatment on development of *Fusarium* head blight of winter wheat (Spitak, 2022)

Fungicides/options, consumption norm, application time		During stage Feekes 11.2			During stage Feekes 11.4		
		FHB incidence, %	severity score (avg)	FHB DDD, %	FHB incidence, %	severity score (avg)	FHB DDD, %
Tilt, 0.5 L ha^{-1}	at Feekes 10.5.1	9.3	1	2.3	14.7	1	3.7
Alto super, 0.5 L ha^{-1}		8.5	1	2.1	13.9	1	3.5
Folicur, 0.5 L ha^{-1}		6.9	1	1.7	11.1	1	2.8
Falcon, 0.8 L ha^{-1}		5.8	1	1.4	9.9	1	2.5
Prosaro, 1.0 L ha^{-1}		4.9	1	1.2	8.9	1	2.2
Untreated check	-	22.3	1.3	7.2	26.8	1.6	10.7

With a single application of fungicides from the triazole group at Feekes 10.5.1, the incidence of FHB decreased compared to the untreated check option, ranging from 4.9% to 9.3% (at Feekes 11.2) and 8.9% to 14.7% (at Feekes 11.4). The degree of disease development ranged from 1.2% to 2.3% and 2.2% to 3.7%, respectively. The highest percentage reduction of FHB was recorded in the options, where plants were sprayed with the fungicides Falcon at 0.8 L ha^{-1} or Prosaro at 1.0 L ha^{-1}.

High incidence and severity of FHB were recorded, especially during the 2023 growing season (see Table 3). The incidence of FHB in the untreated check option was 34.6% during the late milk stage (Feekes 11.2) and increased to 65.3% at harvest (Feekes 11.4). The average severity of the disease ranged from 1.8 (Feekes 11.2) to 2.1 scores (Feekes 11.4), with the degree of disease development ranging from 15.6% to 35.9%, respectively. These findings indicate a very high rate of infection and massive development of FHB. It was also observed that abundant rainfall (84.1 mm) and moderate temperatures (18.8 °C) in July 2023 contributed to the spread of the infection during the waxy ripening stage.

Table 3. Impact of fungicide treatment on development of *Fusarium* head blight of winter wheat (Spitak, 2023)

Fungicides/options, consumption norm, application time			During stage Feekes 11.2			During stage Feekes 11.4		
			FHB incidence, %	severity score (avg)	FHB DDD, %	FHB incidence, *%	severity score (avg)	FHB DDD, %
Tilt		at Feekes 10.5.1	17.1	1.3	5.6	35.7	1.6	14.3
Alto super			16.4	1.3	5.3	33.5	1.6	13.4
Folicur			14.4	1.2	4.3	33.4	1.4	11.7
Falcon			12.1	1.1	3.6	31.7	1.2	9.5
Prosaro			10.4	1.1	3.1	29.7	1.2	8.9
Folicur and Prosaro	at Feekes 10.3	at Feekes 10.5.1	3.7	1	0.9	17.1	1.1	4.7
Falcon and Prosaro			1.7	1	0.4	12.7	1.1	3.5
untreated check	-	-	34.6	1.8	15.6	65.3	2.1	35.9

Our research findings revealed variations in *Fusarium* head blight (FHB) disease severity, incidence, and harmfulness between the 2022 and 2023 growing seasons in Spitak, attributable to differences in weather conditions. The significant development of FHB was correlated with lower average air temperatures from heading to the waxy ripening stage during the June–July months (16.4 and 18.8 °C in 2023) and a notably higher amount of precipitation (107.9 and 84.1 mm), along with high relative humidity (refer to Table 1). Moderate temperatures and abundant rainfall extended the flowering stage, prolonging the plants' susceptibility period (flowering stage), thereby heightening the risk of epidemics.

Our research results align with findings from several studies. According to Parry et al. (1995), a prolonged flowering stage increases the risk of an epidemic. Additionally, the severity of FHB primarily depends on air temperature (Mentewab et al., 2000; Brennan et al., 2005; Nita et al., 2005; Okereke et al., 2016) and humidity levels (Lacey et al., 1999; Cowger et al., 2005; Stenglein, 2009).

The results of our research showed that in 2023, with a single application of triazole fungicides at Feekes 10.5.1, the incidence of *Fusarium* head blight decreased, ranging from 10.4% to 17.1% (at Feekes 11.2) and 29.7% to 35.7% (at Feekes 11.4). Meanwhile, the degree of disease development varied between 3.1% to 5.6% and 8.9% to 14.3%, respectively. However, during years of epidemic FHB development, the degree of disease development with a single application of fungicides reduced below the harmful level (10%) only when plants were sprayed with the fungicides Prosaro or Falcon. In contrast, a single application of fungicides Tilt, Alto Super, and Folicur couldn’t significantly suppress the development of FHB.

Spraying winter wheat twice (at Feekes 10.3 and Feekes 10.5.1) during 2023 significantly reduced the development of FHB. The disease incidence and the degree of disease development ranged from 1.7% to 3.7% and 0.4% to 0.9%, respectively, at the Feekes 11.2 late milk stage, while ranging from 12.7% to 17.1% and 3.5% to 4.7%, respectively, at the Feekes 11.4 harvest stage. These figures represent a rather low index in the case of epidemic development of FHB.

Evaluating the biological efficacy of the used fungicides, we can conclude that when weather conditions during the growing season are not favorable for the development of FHB, Prosaro (applied at a rate of 1.0 L ha^{-1}), Falcon (applied at a rate of 0.8 L ha^{-1}), as well as Folicur (applied at a rate of 0.5 L ha^{-1} demonstrate higher efficacy (ranging from 76.4 to 83.3% at Feekes 11.2 and from 73.8 to 79.4% at harvest, respectively) against FHB with a single application at the beginning of the flowering stage (Feekes 10.5.1, early anthesis). However, the fungicides Tilt (0.5 L ha^{-1}) and Alto super (0.5 L ha^{-1}) exhibited the lowest biological efficacy, ranging from 68.1% to 70.8% at Feeks 11.2, and from 65.4% to 67.6% at harvest, respectively (see Fig. 4). Conversely, Falcon and Prosaro demonstrated the highest biological efficacy, ranging from 80.6 to 83.3% at Feeks 11.2 and from 76.6 to 79.4% at harvest, respectively.

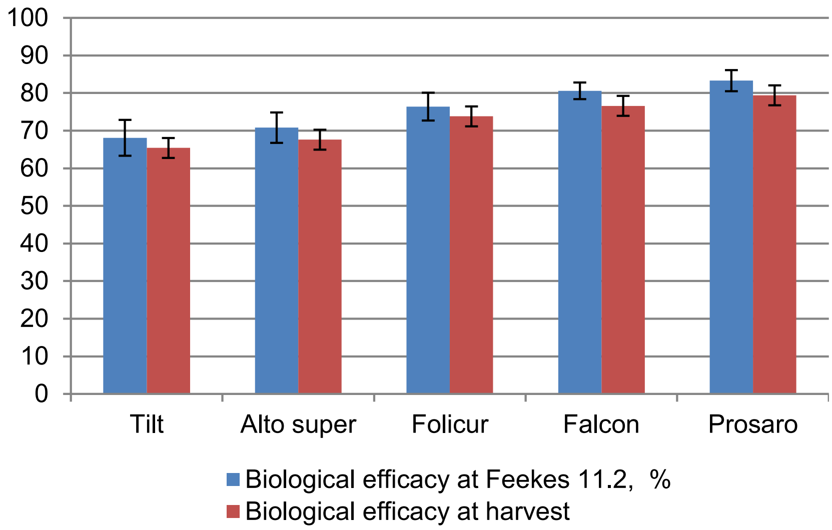

Figure 4. Biological efficacy of fungicides against FHB of winter wheat, 2022: error bars are equivalent to standard deviations.

However, during years of epidemic FHB development, spraying only at the beginning of the flowering stage (Feekes 10.5.1, early anthesis) did not provide high biological efficacy (refer to Fig. 5). These results are consistent with those of Caldwell et al. (2017), indicating that a single fungicide application may not be sufficient to achieve high yields with good seed quality. Two preventive applications during the growing season, the first at Feekes 10.3 (half of heading process completed) with Folicur, 0.5 L ha^{-1} or Falcon, 0.8 L ha^{-1}, and the second at Feekes 10.5.1 (early anthesis) with Prosaro, 1.0 L ha^{-1}, demonstrated high biological efficacy (ranging from 94.2% to 97.4% and 86.9% to 90.3%, respectively) against FHB. However, the Falcon + Prosaro option yielded the highest results.

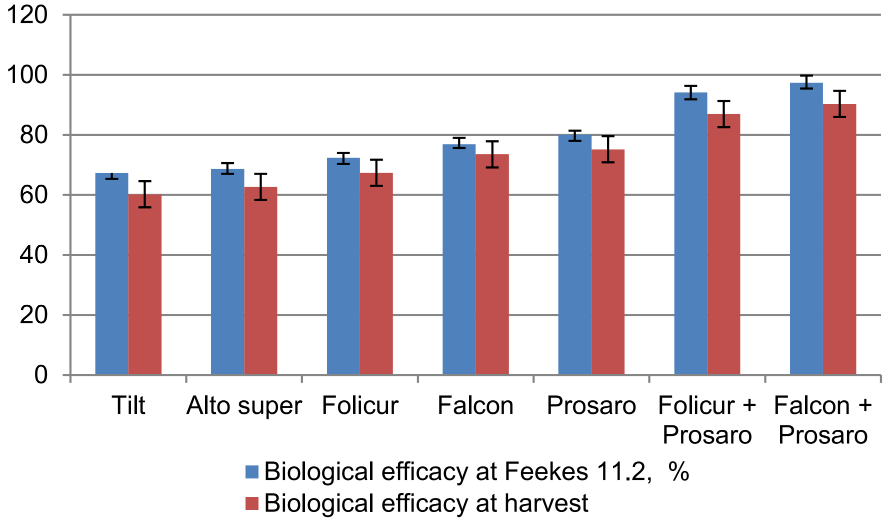

Figure 5. Biological efficacy of fungicides against FHB of winter wheat, 2023: error bars are equivalent to standard deviations.

Analyzing previous research on the efficacy of fungicides against *Fusarium* head blight (FHB) from different chemical groups, it is notable that Bolanos-Carriel et al. (2020) identified triazole and strobilurin fungicides commonly used for controlling FHB and other wheat diseases. The most effective fungicide treatment in reducing FHB severity, damaged kernels, deoxynivalenol (DON) contamination, and yield loss was found to be prothioconazole-containing fungicides (Proline® or Prosaro®) applied during early anthesis, consistently reducing FHB disease severity compared to the untreated/inoculated control (Haidukowski et al., 2012; Bolanos-Carriel et al., 2020). According to other research studies, triazoles such as tebuconazole, metconazole, and prothioconazole (Paul et al., 2008) and benzimidazole fungicides, including carbendazim, control FHB (Zhou et al., 2016; Machado et al., 2017). They inhibit hyphal growth (Hollomon et al., 1998) and regulate DON levels in wheat (Paul et al., 2018). In contrast, strobilurin fungicides are generally ineffective in controlling FHB; moreover, their application increases DON concentration in grain compared to untreated controls (Shah et al., 2018). However, it's worth noting that the control efficacy of carbendazim and other benzimidazole fungicides against *F. graminearum* has declined due to the development of resistance in *F. graminearum* against carbendazim (Liu et al., 2019).

The results of our research in agreement with Maryland Agronomy News, which suggests that tebuconazole-containing Folicur® is less effective compared to prothioconazole-based treatments and should not be used if the risk of FHB is high. Tilt (propiconazole) has become less effective for managing FHB and currently provides poor control.

The effect of the used fungicides on the productivity of winter wheat is presented in Table 4. The yield of winter wheat was 2.12 t ha^{-1} in 2022 and 2.39 t ha^{-1} in 2023 in the untreated check option of the experiment. However, the yield increased to 2.71–3.03 t ha^{-1} in 2022 (an increase of 27.95–42.9%) and to 2.79-3.12 t ha^{-1} in 2023 (an increase of 16.7–30.5%) in the options with a single treatment of fungicides.

Table 4. Effect of preventive fungicides on productivity of winter wheat

Fungicide, consumption norm	2022			2023		
	yield, t ha^{-1}	increase in yield, %	weight of 1,000 kernels, g	yield, t ha^{-1}	increase in yield, %	weight of 1,000 kernels, g
Tilt, 0.5 L ha^{-1}	2.71	27.95	36.5	2.79	16.7	36.2
Alto super, 0.5 L ha^{-1}	2.74	29.44	37.1	2.82	17.8	36.3
Folicur, 0.5 L ha^{-1}	2.86	35.13	38.4	2.87	20.2	36.5
Falcon, 0.8 L ha^{-1}	2.92	37.62	39.3	3.02	26.3	36.8
Prosaro, 1.0 L ha^{-1}	3.03	42.9	40.0	3.12	30.4	37.4
Folicur, 0.5 L ha^{-1} and Prosaro, 1.0 L ha^{-1}	-	-	-	3.33	38.3	39.7
Falcon, 0.8 L ha^{-1} and Prosaro, 1.0 L ha^{-1}	-	-	-	3.51	40,1	40.2
Untreated check	2.12	-	33.5	2.39	-	32.9
LSD_{05}	0.09	-	0.6	0.16	-	1.25

In the options with double preventive spraying of fungicides at Feekes 10.3 and Feekes 10.5.1, the yield of winter wheat ranged from 3.33 to 3.51 t ha^{-1} in 2023, exceeding the results of the untreated check option by 0.94–1.12 t ha^{-1} (an increase of 38.3-40.1%). The highest yield of winter wheat was achieved in the option where Falcon (at a rate of 0.8 L ha^{-1}) was applied first, followed by Prosaro (at a rate of 1.0 L ha^{-1}) for the second spraying.

Similar data were recorded when analyzing the weight of 1,000 kernels. In the case of a single preventive application of fungicides during Feekes 10.5.1 in both 2022 and 2023, the highest weight of 1,000 kernels was recorded when winter wheat was treated with Falcon (39.3 and 36.8 g, in 2022 and 2023, respectively) or Prosaro (40.0 and 37.4 g in 2022 and 2023, respectively), surpassing the results of the untreated check option by 5.8–6.5 and 3.9–4.5 g, respectively. In the case of double preventive spraying with triazole group fungicides during Feekes 10.3 and 10.5.1 in 2023, the highest weight of 1,000 kernels (40.2 g) was observed when plants were treated with Falcon (at a rate of 0.5 L ha^{-1}), and Prosaro (at a rate of 1.0 L ha^{-1}), exceeding the results of the untreated check option by 7.3 g.

Upon comparing the yield data from 2022, it is noteworthy that all experimental variants utilizing fungicide applications exhibited a least significant difference higher than 0.09 t ha^{-1}, ranging from 0.59 to 0.91 t ha^{-1} difference compared to the control option. Additionally, the 1,000 grain weight of all experimental variants demonstrated a least significant difference exceeding 0.6 g, ranging from 3 to 6.5g difference compared to the control option, indicating significant disparity. Particularly promising results in 2022 were observed with a single application of Falcon or Prosaro.

Comparing the yield data from 2023, the least significant difference for all experimental variants with fungicide applications surpassed 0.16 t ha^{-1}, ranging from 0.4 to 0.74 t ha^{-1} (for single applications) and from 0.94 to 1.12 t ha^{-1} (for double applications) difference compared to the control option. Similarly, the 1,000 grain weight of all experimental variants exhibited a least significant difference exceeding 1.25 g, ranging from 3.3 to 4.5 g (for single applications) and from 6.8 to 7.3 g (for double applications) difference compared to the control option, indicating significant differences. Notably, the most promising results in 2022 were achieved with a single application of Falcon or Prosaro, while in 2023, double applications with Folicur + Prosaro or Falcon + Prosaro fungicides proved to be the most effective.

So, we can conclude that based on cultural practices, the application of fungicides has been shown to decrease *Fusarium* head blight incidence, severity, and development, while simultaneously boosting wheat yield. The results corroborate the findings of Kuznetsov et al. (2020), Kolesnikov et al. (2021), and Švarta et al. (2022), demonstrating that the use of pesticides led to an increase in the grain yield of winter wheat.

Based on our research findings, we recommend farmers to apply fungicides to winter wheat at the onset of the flowering stage (Feekes 10.5.1, early anthesis) to effectively control *Fusarium* head blight in rain-fed agriculture. Specifically, we suggest using Falcon at a rate of 0.5 L ha^{-1} or Prosaro at a rate of 1.0 L ha^{-1}. This recommendation is particularly pertinent during years with less favorable weather conditions for disease development. Additionally, during years with the most favorable weather conditions for *Fusarium* head blight development (moderate temperature and abundant rain during heading and flowering stages), it is advisable to implement a double preventive treatment with fungicides against FHB in winter wheat in rain-fed agriculture. The initial application should occur when half of the heading process is completed (Feekes 10.3). We suggest using Folicur at a rate of 0.5 L ha^{-1} or Falcon at a rate of 0.8 L ha^{-1} for this first application. The second application should be conducted during early anthesis (Feekes 10.5.1) using Prosaro at a rate of 1.0 L ha^{-1}. This two-step protocol provides comprehensive protection against *Fusarium* head blight and is especially effective when implemented during the specified growth stages.

It's essential to acknowledge the contentious nature of the data concerning the impact of strobilurins and triazole fungicides on post-harvest grain infection with *Fusarium* spp. and mycotoxin contamination. Butkutė et al. (2008) noted that while the concentration of zearalenone (ZEN) was lower in strobilurin and triazole fungicide-treated plots compared to untreated ones, the concentration of deoxynivalenol (DON) was significantly higher. Despite negligible contamination with T-2 toxin, there was a tendency for it to decrease in grain from fungicide-treated plots. Moreover, the correlation between the percentage of grain kernels infected with *Fusarium* spp. and mycotoxin levels was found to be weak (Butkutė et al., 2008).

In contrast, another study by Bolanos-Carriel et al. (2019) suggested that the reduction in deoxynivalenol (DON) observed in the field from applying a triazole fungicide (Prosaro) at anthesis could be sustained throughout the grain storage period. However, the application of a strobilurin fungicide (Headline) at anthesis was ineffective in reducing DON and even led to an increase during storage. Conversely, DON levels were lower at the beginning of storage and remained stable over time with the use of the triazole fungicide Prosaro, indicating its efficacy in controlling mycotoxins in stored grain (Bolanos-Carriel et al., 2019).

Furthermore, it's noteworthy that fungicides containing strobilurins should not be used beyond flag leaf emergence on wheat because they can potentially increase DON vomitoxin accumulation in the grain (Bonfada et al., 2019; Gaurilèikienë et al., 2005). These findings underscore the complexity of managing *Fusarium* head blight and mycotoxin contamination, emphasizing the importance of careful consideration and monitoring when employing fungicide treatments.

CONCLUSION

Concluding the results of the research, it can be stated that winter wheat is particularly sensitive to *Fusarium* head blight, especially during the flowering stage. Prolonged rains during flowering contribute to the delay of the flowering stage, prolonging the susceptibility of plants thereby increasing the risk of FHB epidemics.

A massive development (epidemic) of *Fusarium* head blight was recorded in Spitak in 2023 due to favorable weather conditions for the development of the pathogen. Abundant rainfall and moderate temperatures contributed to the spread of the infection during the waxy ripening stage as well.

Based on agricultural practices, it is recomended to apply fungicides to winter wheat at the onset of the flowering stage (Feekes 10.5.1, early anthesis), utilizing Falcon at a rate of 0.5 L ha^{-1} or Prosaro® at a rate of 1.0 L ha^{-1} to manage *Fusarium* head blight in rain-fed agriculture. This strategy is particularly crucial during years with less favorable weather conditions for disease development. Implementing these fungicides can potentially increase yields by 37.62% to 42.9% and the weight of 1,000 kernels by 5.8 to 6.5 g, respectively, compared to the untreated check option in the experiment.

The use of a double fungicide treatment is recommended for managing *Fusarium* head blight of winter wheat in rain–fed agriculture, particularly during years with more favorable weather conditions conducive to disease development (moderate temperatures and abundant rain during heading and flowering). This strategy is especially beneficial when integrated with cultural practices, such as those aimed at reducing inoculum levels and optimizing crop health. The first application should be done at Feekes 10.3 (when half of the heading process is completed), using Falcon at a rate of 0.5 L ha^{-1}, followed by a second application at Feekes 10.5.1 (early anthesis) using Prosaro® at a rate of 1.0 L ha^{-1}. Implementing this strategy can potentially increase yields by 40.1% and the weight of 1,000 kernels by 7.3 g compared to the untreated check option in the experiment.

The data acquired will serve as a foundation for ongoing research aimed at enhancing protective strategies against *Fusarium* head blight across various regions of the Republic of Armenia, encompassing both rain-fed and irrigated agricultural systems. Furthermore, this information will play a crucial role in controlling the presence of deoxynivalenol mycotoxin in harvested grains. Additionally, it will serve as essential training material for farmers, equipping them with the knowledge and skills needed to effectively address *Fusarium* head blight in their crops.

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