Comparison of aerial and ground spraying applications in controlling fusarium crown rot in wheat

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Abstract: Fusarium crown rot (FCR) is a chronic disease in many regions of the world in wheat, caused by *Fusarium culmorum*, *Fusarium pseudograminearum,* and *Fusarium graminearum*. The operational efficacy of pesticide applications using unmanned aerial vehicles (UAVs) significantly affects the biological efficacy of the pesticides. This study aimed to compare the effectiveness of unmanned aerial vehicle and field sprayer applications in controlling crown rot diseases frequently observed in wheat crops in the Thrace region, Turkey. A licensed fungicide containing the active ingredients, prochloraz plus trifloxystrobin plus cyproconazole mixture was applied to wheat during the ZGS 27 growth stage. The disease severity, disease incidence, and the effectiveness of fungicide treatment on disease severity (%) were evaluated for *F. culmorum* crown rot disease. The results showed that the severity of the disease during the seedling stage was 11.25% and 18.33% for unmanned aerial vehicle and field sprayer applications, respectively. In the harvest stage, the incidence of disease was 28.33%-39.99% and 48.75%-51.25%, respectively, and the effectiveness of unmanned aerial vehicle application was found to be high, approximately 52%, during the seedling and harvest stages. The unmanned aerial vehicle, acting similarly to the field sprayer, exhibited higher grain quality under conditions of stress from disease. Furthermore, spike weight, grain weight, and number of grains exhibited stronger positive correlations compared to unmanned aerial vehicle treatment. Therefore, unmanned aerial vehicles have promising potential as viable options to manage FCR when the prevailing environmental conditions are not conducive to the use of field sprayer. The results of this research will guide future studies to investigate the efficacy of UAVs on a wider range of pesticides and to further develop the technology to investigate its effectiveness, cost-effectiveness, and sustainability in agricultural applications.

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1 Introduction

Fusarium crown rot (FCR) is a chronic and severe disease in wheat in many regions of the world, caused by *Fusarium culmorum, Fusarium pseudograminearum* (group I) (i.e., Gibberella coronicola), and *Fusarium graminearum* Schwabe (group II) (i.e., G. zeae). FCR pathogens can also infect other cereal crops such as maize and barley[1-3]. In regions where the disease caused by *Fusarium* species is severe, crop reduction has been reported to reach levels of 50%-70%[4-7]. In cases where FCR-infected plants (Fusarium Crown Rot) are simultaneously coinfected with Fusarium head blight (FHB), there is a greater likelihood that wheat seeds become contaminated with fungal toxins such as deoxynivalenol (DON) and nivalenol (NIV). This presents a substantial hazard to the health of both human consumers and livestock[8]. In surveys conducted in different regions of Turkey, *Fusarium culmorum* has been identified as the most common pathogen that causes FCR and as a source of severe infections for many years[9-11]. Despite the extensive adoption of soil tillage in wheat farming in Turkey, the incidence and severity of *F. culmorum* crown rot have worsened due to suitable climate conditions. FCR has been reported to cause yield losses of up to 50% in Turkey's commercial areas of winter wheat[12]. Consequently, it has become imperative to implement fungicide applications. Fungicide applications are carried out with a field sprayer. Unmanned aerial vehicles (UAVs) are commonly used for applications such as imaging, remote sensing, defense, industry, security, and firefighting in the world. After the defense and security sectors, UAVs introduced for civilian use have also begun to spread in agriculture. According to the International UAV Association, it is estimated that 80% of UAVs worldwide will be used in agriculture soon. In recent years, UAVs equipped with a tank and spraying system have become increasingly popular for pesticide applications[13]. Agricultural UAVs have become attractive to farmers due to their advantages, such as reducing field traffic, facilitating pesticide applications on steep and difficult terrain, and reducing water usage. Operational parameters during pesticide applications using UAVs significantly affect the biological efficacy of the pesticides. When applications are carried out with the correct parameters, UAVs can achieve biological efficacy similar to conventional spraying machines[14-16]. Since the use of UAVs in pesticide applications first became widespread, scientists have been researching the most effective and efficient application parameters. Different researchers have obtained similar results in spray trials on various crops. In these studies, the average flight parameter of 15-

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20L/hm², a height of 2.5-3.0 m from the upper part of the plant, and a speed of 3-4 m/s have been recommended[17-20]. The type and arrangement of the UAV's rotor are important for the success of fungicide applications. Martin et al. reported that with the help of the downward airflow generated by the UAV, droplets can reach the lower leaves of the plant[21]. However, the danger of this airflow is that it can also cause droplets to drift[22]. Compared to conventional applications, a lower application rate can lead to less pesticide coverage on the target surface and a decrease in the efficacy of the pesticides currently used. The effectiveness of controlling pests and diseases is the most important criterion in chemical control[23]. The success of applications made in agricultural unmanned aerial vehicles using different pesticides in different plants is observed through scientific studies. Qin et al.[24]achieved a 92% efficacy rate with a spraying UAV, and Lou et al.[25]obtained a biological efficacy rate of 61%-63%. The researchers obtained a droplet distribution and biological efficacy similar to conventional applications in their studies on wheat spraying UAVs[23,26,27].

In reviewing the studies, it is observed that there is a lack of literature on the success of unmanned aerial vehicles (UAVs) in the application of fungicides against wheat Fusarium crown rot disease. This study aims to measure disease severity and wheat quality parameters in order to compare the efficacy of fungicide applications made with the most preferred field sprayer type and those made with an agricultural unmanned aerial vehicle in controlling root and crown rot diseases frequently observed in wheat crops in the Thrace region.

2 Materials and methods

2.1 Instruments

Unmanned Aerial Vehicle (UAV): In the experiment, a UAV was used for the DJI Agras MG-1P 8-rotor 4-nozzle spraying UAV with a 10-liter tank capacity (Figure 1a). The spray nozzles used in the UAV were a Tee jet brand model (Spraying Systems) XR 11001VS, placed in the corners of a square with two in front and two in the back, according to the direction of travel. The droplet sizes generated by these nozzles range from 106-235 μm[28]. Spray nozzles were positioned parallel to the spray direction. The UAV was controlled by remote control, and the flight and spraying parameters could be adjusted from the remote control's screen. Before spraying, the locations and corner points of the target parcels were determined using remote control position data, and flight routes were automatically generated. The DJI D-RTK2 RTK device was used during the flight to increase the location accuracy. The UAV carried out spraying with a height of 2 cm and location accuracy with data received from the RTK device. During spraying, the UAV height was set at 2 m, the spraying rate was 20 L/hm², and the forward speed was set at 11 km/h. The pesticide spraying UAV carried out the spraying by progressing to a preset route in the target parcel during the application flight. During each trial, the UAV took off from the starting point, started spraying the parcel from 5 m on the planned route, turned back from the end of the parcel, and returned while the spraying stopped 5 m away from the boundary of the parcel, and finally returned to the starting point. Starting and stopping spraying from 5 m from the parcel was to prevent the irregularity of the spray rate that occurs during open-close operations from affecting mammals.

Field Sprayer (FS): The field sprayer used in the experiment is a tractor-mounted type with 800-liter tank capacity, a membrane pump, and 24 AIXR110003 nozzles with 12 m boom (Nedimler Co.) (Figure 1b). Sprayers with these specifications are found to be the most commonly used field sprayers in the Thrace region, Turkey[29]. In applications made with a field sprayer, since the parcel widths are the same as the working width of the sprayer, the tractor's travel line is determined from the middle of the plot, spraying is carried out at a fixed speed, pressure, and rate during the flight, and the application is terminated at the end of the plot.

Spraying was carried out with a spraying rate of 200 L/hm² at 3 bar pressure and a tractor speed of 10 km/h. The spraying parameters are listed in Table 1.

a. UAV b. Field sprayer

Figure 1 UAV and field sprayer

Table 1 Spraying parameters of UAV and FS in the wheat plots

Spraying equip.	Nozzle type	Pressure/bar	Forward speed/km·h^{-1}	Application height/m	Spray rate/L·hm^{-2}
UAV	XR11001VS	3.5	11	2	20
FS	AIXR11003	3	10	0.5	200

2.2 Fungicides

Wheat seeds not infected with fungi were treated with a fungicide containing 40 g of pyraclostrobin plus 80 g of triticonazole (Insure Perform FS, BASF). A licensed fungicide containing 250 g/L of prochloraz plus 75 g/L trifloxystrobin plus 50 g/L of cyproconazole (Basking 1 L/hm² Agrobest Turkey) active ingredient was applied to control root and crown rot disease in wheat during the ZGS 27 growth stage (20th March, 2022)[30]. During the application, the temperature was measured at 15°C, the humidity was 69%, and the wind speed was 5.1 km/h. Meteorological data was collected during the application using a Lutron AM 4202 model anemometer and a Testo brand 605-H1 thermo-hygrometer at a height of 2 m, and averages were taken.

2.3 Field trials

The field trial was conducted in the Tekirdağ Namık Kemal University trial area in the 2021-2022 seasons (40°59′30.25′′N 27°35′3.97′′E). The bread wheat variety "Flamura 85", previously found to be susceptible to *Fusarium culmorum*, was used in the trial. To provide infected seeds with the pathogen, wheat in the ZGS61 flowering stage was artificially inoculated with 1×10^5 spores/ml of *Fusarium culmorum* S-14 isolated under field conditions in the growing season 2019-2020. The trial plots were formed as follows: Infected seed control (IC), non-infected seed + seed fungicide application as general control (GC), infected seed + UAV fungicide application (UAV), and infected seed + field sprayer application (FS). The placement of the trial plots in the field was determined using the randomized block method with three replicates.

The size of each plot was determined at 25 m×12 m to facilitate maneuverability, RTK positioning accuracy, and uniformity of UAV and FS applications. Since the 12 m width is equal to the working width of the field sprayer, the field sprayer can be used to apply the treatment in a single pass in the plots where the field sprayer is used. The top 10 m space was left at the top and bottom of the plot for the UAV's take-off, landing, and turning maneuvers, for the tractor to maneuver. A 12 m gap was left between the two plots to minimize the effect of spray drift, and wheat was seeded in 25 m×6 m plots in these areas as a buffer zone (Figure 2).

The sowing rate was 180 kg/hm^2 and the spacing between rows was 13 cm. Plant protection and fertilization practices were carried out as in normal wheat cultivation throughout the growing season. Before sowing, 200 kg/hm^2 of 12-20-0 NPK organomineral fertilizer was used as a base fertilizer. Pyroxasulfone (Kelt WG 85, Bayer Crop Science), an effective soil herbicide, was applied to control weeds after sowing. During the growing season, 150 kg/hm^2 of 46% urea fertilizer was applied on 5 March, 2022, and 150 kg/hm^2 of 46% urea top dressing was applied on 4 April, 2022.

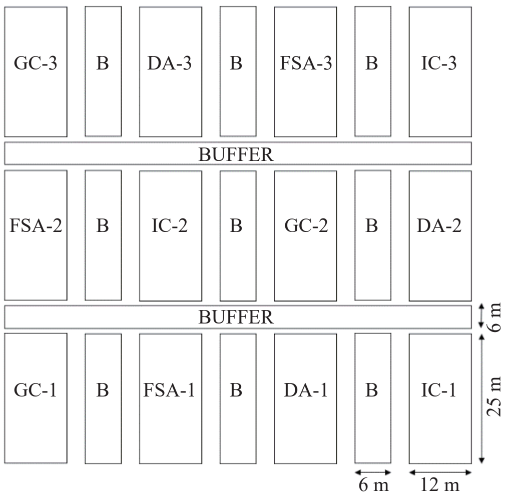


Figure 2 Layout of trial plots

2.4 Droplet analysis

Water-sensitive papers measuring 26 mm×76 mm (Novartis, Syngenta Crop Protection, 2021) were used to investigate droplet distribution in pesticide applications using UAVs in hazelnut orchards. To monitor droplet distribution in different areas of the plants, we attached water-sensitive paper with a clip to one plant in each section at three different heights along the vertical axis of the plots. Three samples were taken at three different points with three replicates in each plot. The areas allocated to the crop are shown inFigure 3. After each flight, the water-sensitive papers on the sprayed trees were collected and placed in airtight and moisture-proof packages. After the experimental flights were completed, all water-sensitive papers were scanned with a resolution of 600 dpi and transferred to a computer. DepositScan software was used to calculate droplet diameters, coverage area percentages, droplet counts per unit area, and total droplet counts in water-sensitive articles[31]. The measured values on each water-sensitive paper for each experiment were transferred to Microsoft Excel Software and plotted on graphs.

Figure 3 Water-sensitive paper placed on a leaf of wheat plot

2.5 Severity and incidence of the disease

The severity of FCR disease was evaluated twice, during seedling (ZGS 27) and harvest periods. During the evaluation of the seedling period, 25 plants were removed from each plot and rinsed with tap water. The lesions resulting from pathogen activity during this phase were identified applying the modified scale 0-5 as follows: 0 for a healthy plant; 1 for necrotic area less than 25%; 2 for necrotic area between 25%-50%; 3 for necrotic lesions ranging from 51%-75%; 4 for necrotic lesion exceeding 75%; 5 for a completely dead plant, following the criteria outlined by Wildermuth and McNamara[32]. In evaluating the severity of the disease during the harvest period, a scale of 0-5 (0: no lesions; 1: one or two lesions covering <10%; 2: l0%-25%; 3: 25%-50%; 4: 50%-99%; 5: 100% of the sub-crowned internode) was used to evaluate the plants based on the necrotic area of the roots and the root collar[33]. Disease severity was assessed based on the methodology established by Townsend and Heuberger in 1943[34]. The incidence of disease (DI) was evaluated using the formula (DI= number of diseased plants/total number of plants).

2.6 Harvest Assessment

From each plot, 25 plants were randomly selected and the plant height (cm) (the distance from the top of the head to the soil), plant weight (g), spike weight (g), the number of grains, and grain weight (g) were determined. The thousand-weight kernels (TGW, g) and grain yields (GY, kg/hm^2) were determined following the approved methods of the American Association of Cereal Chemists[35]from a homogeneous sample of each plot after harvest (ZGS 90-92) using a small plot harvester (Hege Maschinen, Niederlassung, Germany).

2.7 Grain quality analysis

Grain protein ratio (GP, %)[36], normal sedimentation values (NS, ml), late sedimentation (LS, mL), wet gluten (WG, %), gluten index (GI, %), and moisture (%)[37,38]were determined in 1 kg seed samples taken from each plot.

2.8 Data analysis

The data distribution was evaluated using the Shapiro-Wilk W-test. The obtained data for disease evaluation and grain quality parameters showed a normal distribution; however, since the obtained data for harvest did not show a normal distribution, the comparison between treatments (UAV, FS, IC, GC) was performed by the Mann-Whitney U test for those traits. Analysis of variance (ANOVA) for disease evaluation and grain quality parameters was analyzed for statistically significant differences using Fisher's least significant difference (LSD) test (α=0.05). SPSS 21.0 software (SPSS Inc., Chicago, IL, ABD) was used for all data evaluated.

3 Results and discussion

3.1 Droplet analysis

The experimental results related to these values are shown in the table. As listed in Table 2, there has been a decrease in all measured values in applications using UAVs. The values for $Dv_{0.1}$, $Dv_{0.5}$, and $Dv_{0.9}$ in field spray applications are 258.5 μm, 608.5 μm, and 1049 μm, respectively, while they are 130.8 μm, 226.5 μm, and 353 μm in applications using UAVs. The results obtained from the biological studies were analyzed separately. Similar successes were particularly observed, highlighting the success of reduced pesticide usage. Furthermore, when the surface coverage values were compared, the overlap of the droplets and the higher number of droplets per unit area increased this value. In UAV applications, this value was 1.7%, while in field sprayers it was 21.5%. The coverage value of UAV applications is very low. In studies conducted on pesticide applications with UAVs, we see that the coverage rate of pesticide applications with UAVs varies between 0.1% and

4.0%[14,17,18,26]. In this study, although the droplet density was 26 deposits/cm², the average diameter of the droplets produced by the UAV was classified as fine, so the coating percentage was low.

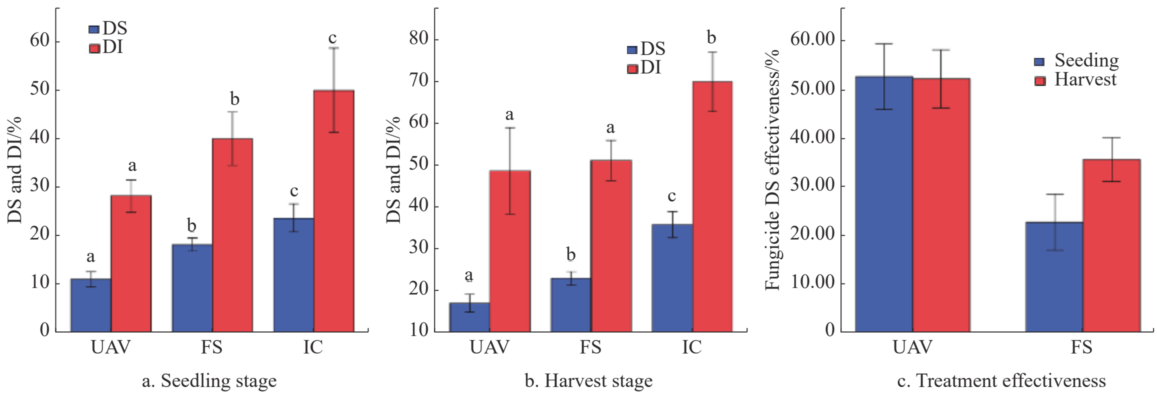
Table 2 Droplet parameters of UAV and FS in the wheat field experiment

Droplet Parameters	UAV		FS	
	Mean	CV%	Mean	CV%
$Dv_{0.1}/\mu m$	130.8	4.5	258.5	15.0
$Dv_{0.5}/\mu m$	226.5	14.8	608.5	12.2
$Dv_{0.9}/\mu m$	353.0	27.4	1049.0	14.8
Coverage/%	1.7	73.1	21.5	32.0
Deposits/cm²	26.0	61.5	101.5	14.0

In ASAE S572, the droplet sizes are classified into different categories: very fine (101-200 μm), fine (201-300 μm), medium (302-400 μm), coarse, and very coarse. According to this standard, medium and coarse droplets are recommended for systemic fungicides. The diameters of the droplets generated by field sprayers are classified as very coarse. The reason for this is that the nozzles used are air induction nozzles. Looking at the table given by the nozzle manufacturer, it can be seen that droplets at 3 bar pressure and 200 L/hm² spray rate are classified as extra coarse (TeeJet Technologies, Spraying System Co., Wheaton, IL, USA). While volumetric droplet size values are generally considered, the drift potential depends not only on the volumetric median droplet size ($Dv_{0.5}$) but also on the entire spectrum of droplet sizes. The higher the $Dv_{0.1}$ value, the lower the probability of drift. The larger the $Dv_{0.9}$ value, the fewer droplets are needed to provide sufficient coverage[39]. These characteristics provide information about the structure of the pulverization. For effective management of weeds, pests, and diseases, meticulous consideration of the optimal dosage of pesticides, selection of the most appropriate droplet size, and consideration of prevailing weather conditions are imperative. This approach is instrumental in ensuring enhanced coverage, adhesion, dispersion, and absorption of the droplets on the target surface. The droplet density of the sprayed surfaces was found to be 26 droplets/cm² for the UAV application, while it was 102 droplets/cm² for the field sprayer application. However, previous studies suggest 20-30 droplets/cm² for successful fungicide application[39]. This result indicates that the same success can be achieved with fewer droplets. The development and assessment of aerial application techniques that improve the deposition of fungicides on the surface of treated plants is critical to disease control. Many studies on aerial applications in cotton, maize, and weed control have indicated that the optimal combinations of spray rate and drop size vary based on the specific disease, pest, or target site[40,41]. Zhang et al.[42]found that the best spraying for deposition in wheat ears for *Fusarium graminearum* head blight occurred in hydraulic nozzles with a spray rate of18.7 L/hm² and an average volumetric median diameter (VMD) of 350 μm. In our study, it was determined as a spray rate of 20 L/hm² and 230 μm VMD of 230 m droplets. Therefore, all research on UAV-based fungicide applications for plant disease control guides aerial application.

3.2 FCR disease evaluation

The disease severity (%), disease incidence (%), and the effect of treatment on disease severity (%) were evaluated in seedlings developed from naturally infected wheat seeds with *F. culmorum* in two stages, namely seedling stage (ZGS 27) and harvest stage, for the F-85 cultivar (Figure 4). Significant differences (p=0.05) in disease severity were detected between the UAV and FS applications. The disease severity during the seedling stage was found to be 11.25% and 18.33% for UAV and FS applications, respectively. During the harvest stage, disease severity was determined to be 17.18% for the UAV application and 23.12% for the FS application. However, disease severity in the infected control was found to be high, with values of 23.75% and 35.93% during the seedling and harvest stages, respectively, compared to treatment.



Note: Mean±standard error of the mean (SEM). Columns with different letters indicate statistical differences according to the LSD test at p=0.05 as separately in DS and DI. All values are means of three replicas (n=75).

Figure 4 Disease severity (DS), disease incidence (DI), and effectiveness of fungicide application with UAV and FS

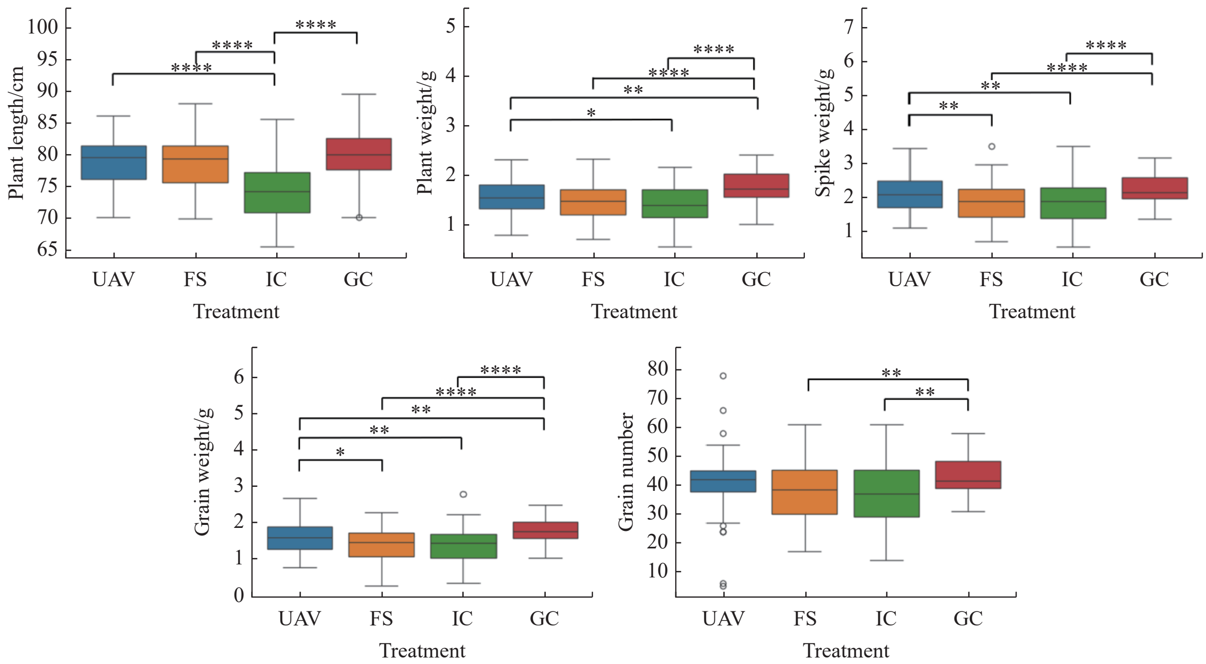
The disease incidence was determined to be 28.33%-39.99% and 48.75%-51.25% for UAV and field sprayer applications during the seedling and harvest stages, respectively. The disease incidence in the infected control was identified as 50% during the seedling stage and 70% during the harvest stage. When the effectiveness of the FS and UAV application was compared, the effectiveness of the UAV application was found to be high, approximately 52%, during the seedling and harvest stages. The effectiveness of FS application was found to be 22.82% during the seedling stage and 35.63% during the harvest stage.

FCR is considered one of the most important fungal diseases in Turkey. The application of fungicides to seeds can change the efficacy of seedling-stage fungicide applications[43]. However, since fungicide seed treatments do not maintain their efficacy much beyond the seedling stage, the effectiveness of chemical control is limited to the early stages of the wheat growth cycle[44]. Therefore, fungicide applications are mandatory for our region during the wheat emergence period, as favorable climatic conditions in the

Thrace region promote severe infections by the disease agent[45]. For FCR control, prochloraz plus trifloxystrobin plus cyproconazole (Basking 1 L/hm², Agrobest Turkey), licensed in Turkey, was found to be more effective in suppressing the severity of wheat disease when used as a UAV application. Indeed, some researchers have found that aerial spraying provides better mobility and more effective insecticide application than ground application[46,47]. In this study, UAV provided an effective fungicide application for the control of *F. culmorum*. It is possible to further increase the spraying efficiency of UAVs with appropriate operating mode and adjuvant use[48,49].

3.3 Harvest assessment

Plant height (cm), plant weight (g), spike weight (g), grain weight (g), and grain number were determined during the harvest season in 2022 (Figure 5). There is no statistically significant difference in plant length, plant weight, and grain number between the UAV and FS treatments, indicating that both treatments produce similar effects on these parameters. A statistically significant difference in grain weight was observed between the UAV and FS treatments (p=0.014), indicating that the UAV treatment resulted in heavier grains compared to the FS treatment. A statistically significant difference in the spike weight was observed between the UAV and FS treatments (p=0.009), indicating that the UAV treatment resulted in a higher spike weight than the FS treatment. This result suggests that while plant growth is affected by treatment, UAVs may offer advantages in certain yield-related parameters.



Note: The boxes represent the distribution of values among the groups, indicating the median value and the range (interquartile range, IQR) between the 25th and 75th percentiles. The horizontal line within the box represents the median value. The stars on the graph indicate statistically significant differences between treatments, determined using the Mann-Whitney U test. The number of stars varies according to the p values (*: p≤0.05; **: p≤0.01; ***: p≤0.001; ****: p≤0.0001).

Figure 5 Comparison of grain weight, grain number, spike weight, plant weight, and plant length in different treatment groups

3.4 Grain quality parameters

Wheat Grain Protein Content (GP) (%), Wet Gluten (WG) (%), Index (%), Normal Sedimentation (NS) (%), Late Sedimentation (LS) (%), Hectoliter Weight (HW) (Kg), Moisture (%), Thousand Grain Weight (TGW) (g), and Grain Yield (GY) (kg/hm²) after the application of the active ingredient fungicide prochloraz plus trifloxystrobin plus cyproconazole for root collar infections with UAV and field sprayer during the growing season 2022 are presented inTable 3.

The UAV application has shown a statistically significant difference in the gluten index (GI) and thousand grain weight (TGW) parameters as compared to the FS application. In particular, the UAV application exhibited higher values, with a GI of 94.67% and a TGW of 39.13 g, compared to the FS application, which demonstrated an 88.33% GI and a 36.53 g TGW. Furthermore, the UAV application demonstrated a moisture content comparable to that observed in the FS application. On the contrary, the FS application yielded superior results in parameters such as WG and GY. The FS application was found to show higher values, with a WG content of 32.33% and a GY of 491.33 kg/hm², compared to theUAVapplication,whichrecordedaWGcontentof27.67%andaGYof 462.62 kg/hm². These results indicate that both applications have the potential to positively influence wheat quality and yield in the presence of disease stress.

Any stress conditions during the grain filling stage (salinity, drought, extreme temperatures, waterlogging) can decrease grain yield and cause changes in the composition and quality of the grains[50].Wheatyieldandqualityparametersincludeproteincontent(GP), wet gluten (WG), normal sedimentation (NS), late sedimentation (LS), hectoliter weight (HW), gluten index (GI), moisture content, thousand grain weight (TGW), and grain yield (GY). Each of these parameters has an important impact on the storage capacity and nutritional value of processed wheat[51,52].

The prevalence of *Fusarium culmorum* crown rot infection has been identified as a major problem in our region, particularly in terms of yield and grain quality[53,54]. In our study, the biotic stress type *F. culmorum* resulted in a notable decrease in WG, NS, LS content, TGW, and IC yield. Furthermore, it was observed that the UAV, acting similarly to the FS, exhibited a higher grain quality under disease-stress conditions. The study revealed that unmanned aerial vehicles (UAVs) exhibited inferior performance in specific quality parameters, particularly regarding wet gluten content and grain yield, compared to FS. This suggests that the efficacy of UAV applications could be improved by optimizing operational parameters and the use of adjuvants.

Table 3 Grain protein content (GP), wet gluten content (WG), normal sedimentation (NS), late sedimentation (LS), hectoliter weight (HT), gluten index (GI), moisture, thousand grain weight (TGW), and grain yield (GY) in the experiment conducted to determine the effects on grain quality parameters of fungicide application with UAV and FS

Treatment	GP/%	WG/%	NS/%	LS/%	HW/kg	GI/%	Moisture/%	TGW/g	GY/kg·hm^{-2}
UAV	13.46^{b*}	27.67^{b}	50.67^{b}	47.00^{a}	78.49^{b}	94.67^{ab}	13.46^{a}	39.13^{a}	4626.2^{b}
TP	14.80^{b}	32.33^{a}	60.00^{a}	49.33^{a}	78.95^{ab}	88.33^{b}	12.83^{b}	36.53^{b}	4913.3^{a}
IC	11.90^{c}	20.66^{c}	39.00^{c}	43.66^{a}	79.00^{b}	95.67^{a}	13.40^{a}	37.77^{ab}	4111.1^{c}
GC	15.26^{a}	34.33^{a}	62.67^{a}	56.33^{b}	79.00^{a}	89.33^{ab}	12.37^{c}	36.80^{b}	4756.7^{ab}

Note: *Means followed by the same letter within a column are not significantly different according to the least significant difference (LSD) test (p=0.05).

3.5 Correlation analysis

The correlations were individually assessed for UAV and FS (Figure 6). In UAV treatment, a highly significant positive correlation was observed between spike weight and grain weight (r=0.87, p<0.0001), indicating that an increase in spike weight is associated with a corresponding increase in grain weight. A positive correlation (r=0.53, p<0.0001) was observed between plant length and plant weight, indicating that taller plants tend to have higher weights. In the FS treatment, strong correlations were identified between spike weight and grain weight (r=0.97, p<0.0001) and between spike weight and grain number (r=0.88, p<0.0001). A highly significant positive correlation (r=0.84, p<0.0001) was identified between plant and spike weights, indicating a close relationship between the two variables. Furthermore, a strong positive correlation (r=0.80, p<0.0001) was observed between the number of grains and the weight of the spikes, indicating that an increase in the number of grains in the spikes leads to a corresponding increase in the spike weight. These strong correlations underscore the intimate relationship between plant weight and spike weight.

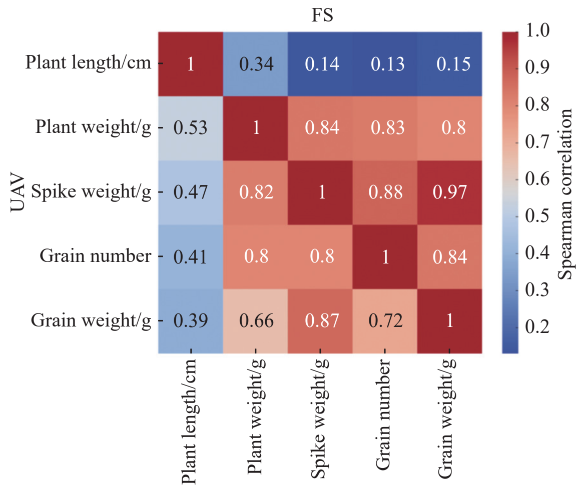


Figure 6 Spearman correlation coefficients between plant length (cm), plant weight (g), spike weight (g), grain number, and grain weight (g) for UAV (unmanned aerial vehicle) (left) and FS (field sprayer) (right) applications, respectively

These findings contribute to our current understanding of the impact of UAV and FS applications on crop characteristics. The significant correlation between yield-related parameters, such as spike weight and grain weight in UAV applications, highlights the potential of this method to improve crop yield. Similarly, the high correlation between the number of grains and spike weight in FS application confirms the positive impact on yield outcomes. The correlation analysis provides valuable information on the impact of UAV and FS applications on plant characteristics and yield parameters. It suggests that each method offers unique advantages in improving agricultural productivity. Future research should aim to validate these findings and further investigate these relationships, which will aid in identifying the most effective methods of agricultural application. This analysis provides critical information on the impact of these two different treatment methods on plant characteristics, highlighting the importance of considering the differences between UAV and FS treatments in studies of plant growth and yield.

A positive correlation, indicated by a red shade, denotes an increase in one variable accompanied by another. Statistically significant correlations are indicated by p values.

4 Conclusions

The results of this study, which aimed to evaluate the efficacy of unmanned aerial vehicles (UAVs) in controlling Fusarium crown rot (FCR) disease compared to field sprayers (FS), indicate that UAVs are markedly more effective than FS in reducing disease severity and incidence. Particularly, the deployment of UAVs resulted in a reduction in disease severity during both the seedling and harvest stages. The results revealed that the severity of the disease during the seedling stage was 11.25% for UAV applications, compared to 18.33% for FS applications. At the harvest stage, the severity was 17.18% for UAV and 23.12% for FS applications. The disease incidence at the seedling stage was 28.33%-39.99% for UAV applications and 48.75%-51.25% for FS applications. During the harvest stage, the disease incidence for UAV applications was significantly lower, demonstrating approximately 52% effectiveness in disease control, compared to 35.63% effectiveness for FS applications.

Concerning yield components, the spike weight for UAV applications was 1.12 g, while for FS applications it was 0.98 g. Similarly, the grain weight was higher in UAV applications (0.98 g) compared to FS applications (0.87 g). The number of grains per spike was greater in UAV applications (28.3) compared to FS applications (24.5). Furthermore, UAV applications demonstrated operational advantages, including reduced water usage, shorter application times, and enhanced operator safety. The finer droplet size produced by UAVs facilitated more comprehensive fungicide coverage on plant surfaces. This study represents a notable advancement in the field by identifying the beneficial effects of UAV applications on wheat quality under disease conditions.

These findings indicate that UAVs represent a viable and superior alternative to conventional FS methods for pesticide application. However, more research is required to investigate the efficacy of UAVs across a wider range of plant diseases and to develop the technology for broader pesticide applications. It would be beneficial for future studies to focus on assessing the cost-effectiveness and sustainability of UAVs in agricultural practices.

To conclude, this study highlights the potential of UAVs as an effective tool in managing agricultural pests, offering advantages over traditional methods under specific conditions. The ongoing examination of unmanned aerial vehicle (UAV) applications holds promise in enhancing sustainability, efficiency, and crop quality.

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