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Research Article

Integrated Management of Fusarium Head Blight in Wheat Caused by *Fusarium graminearum* Using Tebuconazole, Zinc, and Plant Growth Regulators

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ABSTRACT

Fusarium head blight (FHB), caused by *Fusarium graminearum*, adversely affects wheat growth and yield. This study evaluated the effects of fungicide, zinc, gibberellin, and salicylic acid treatments on the growth and yield-related traits of two wheat cultivars, Wafiya and Adana 98. Treatment responses varied among the measured parameters. The combined application of tebuconazole, zinc, and gibberellin produced the maximum plant height (88.5 cm), root length (12.5 cm), and leaf area (21.5 m^2), whereas the infected control recorded the minimum values of 68.0 cm, 5.5 cm, and 13.3 m^2, respectively. Salicylic acid treatment following *F. graminearum* inoculation resulted in the highest fresh vegetative weight (40.0 g), compared with 20.5 g in the infected control. The maximum dry weight (22.5 g) was obtained with tebuconazole + nano-zinc treatment, while tebuconazole + gibberellin treatment produced the highest 100-grain weight (5.75 g), compared with 11.5 g and 4.0 g, respectively, in the infected control. At the cultivar level, Wafiya generally exhibited better vegetative growth and biomass accumulation than Adana 98, although their 100-grain weights did not differ significantly. These findings suggest that combining fungicide and growth-promoting inputs may improve wheat performance under FHB pressure, while salicylic acid may contribute to maintaining vegetative growth. Further validation using disease severity, mycotoxin levels, and grain yield measurements is needed to establish treatment efficacy and practical applicability.

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Introduction

Wheat (*Triticum aestivum* L.) is considered as one of the most significant strategic cereal crops widely cultivated in the Mediterranean countries and Iraq, playing a pivotal role in agricultural sustainability, national economy and food security. In Iraq, wheat production was estimated at 6,238,392 tons during the winter season 2020 (Central Statistical Organization of Iraq, 2020). Instead of its significance in human diet, wheat production is threatened by various biotic and abiotic issues such as insufficient agricultural land, shortage of water and the rising incidence, severity and prevalence of wheat diseases especially fungal diseases. In such a situation, enhancing production per unit land area, also called vertical expansion, is the only way to increase wheat production without expanding cultivated land in proportion to the rising demand for wheat.

To increase wheat productivity, integrated wheat

agronomic and plant protection management including enhancement of plant growth, strengthening physiological processes and reducing the negative impacts of biotic and abiotic stresses are essential. Use of essential micronutrients, such as zinc (Zn), may lead to better crop performance as Zn is known to be important in many of its physiological and biochemical functions such as photosynthesis, enzyme activation, carbohydrate metabolism, protein synthesis, and plant growth regulation. Moreover, sufficient zinc nutrition is important for the production of plant pigments, efficient translocation of assimilates from source tissues to sink organs and reproductive development, which lead to better growth and yield formation (Martin, 2002). The efficiency of zinc application is, however, affected by genotype of the crops, nutrient status of the soil, mode of its application and environmental conditions.

Fusarium head blight (FHB), among the major biotic limitations threatening wheat production, is a major fungal disease which has a detrimental effect on grain quality and yield. It is caused by several *Fusarium* species, with *Fusarium graminearum* being one of the most important plant pathogens causing FHB globally. The disease has been reported from wheat-growing areas for over 100 years and still remains a significant problem for cereal production (Bai et al., 2018). Infection can cause a reduction in grain development, result in lower grain yields and negatively impact the physical and nutritional traits of the harvested wheat. In addition, depending upon environmental conditions and the strain of the fungus, *F. graminearum* has the ability to produce mycotoxins, such as zearalenone (ZEA) and deoxynivalenol (DON). These toxins can infect the harvested grains and cause serious health issues to humans and animals, adding to the economic and agricultural impact of the disease (Dweba et al., 2017). Ibrahim, (2018) reported *F. graminearum* as one of the commonly isolated *Fusarium* spp. that are highly pathogenic to wheat seeds. Furthermore, fungal infections, mycotoxin contamination and losses in crop yields and quality are also caused by various *Fusarium* species which cause significant losses in cereal and other crop commodities (Al-Jbouri et al., 2019; Anbih et al., 2022; Mohammed and Al-Fahd, 2023).

For effective management of FHB, approaches that limit pathogen build-up and disease severity, while promoting crop growth and productivity, are needed. A systemic fungicide, tebuconazole, which belongs to the triazole group of fungicides, is extensively applied for suppressing these fungal pathogens. This fungicide acts by inhibiting the biosynthesis of ergosterol, a critical step in the process of cell membrane formation in susceptible fungal pathogens. However, its efficacy against FHB is dependent on the time of application, pathogen resistance/susceptibility, environment, and severity of infection. Other complementary strategies such as the use of micronutrients and plant growth regulators can also be beneficial in sustaining the physiological activities and performance of the plants under pathogen stress. Gibberellic acid (GA_3) controls a number of plant growth and developmental processes such as leaf expansion, stem elongation, and reproductive processes, while salicylic acid (SA) plays a role in plant defense signaling and triggering defense related responses to pathogens. Supplementation with zinc may also be effective in maintaining normal physiological functions and in enhancing tolerance to stress when plants are zinc deficient. However, cultivars, treatment combinations, application rates and severity of pathogen infection may influence the response to these treatments.

The combination of fungicide application together with plant growth regulators and zinc could thus be a complementary approach to control FHB and reduce its impact on wheat growth and yield-related traits. The efficacy of these treatments, alone or in combination, however, needs to be systematically evaluated under *F. graminearum* infection.

Moreover, variations among cultivars can affect the development of disease, response of treatments and maintenance of yield components. Hence, the current study was aimed to determine the effect of *F. graminearum* infection on specific growth and yield parameters of two cultivars of wheat namely Adana 98 and Wafiya, and to evaluate the individual and combined effects of tebuconazole, Zn, gibberellic acid and salicylic acid on growth losses and 100-grain weight due to *F. graminearum*. The study was also designed to compare the reaction of these two wheat cultivars to fungal infection and to find the cultivar that was relatively more tolerant under the prevailing experimental conditions in order to develop integrated management strategies for FHB in wheat.

Materials and Methods

Sample collection

In 2021-2022, wheat plants showing typical symptoms including chlorosis, reduced tillering, stunted growth, and brown internodes were gathered from various wheat

fields in Al-Shirqat district, Salah Al-Din province, Iraq. Samples were collected and brought to the laboratory where the pathogens were isolated and identified.

Isolation and morphological identification of the pathogen

The diseased samples were thoroughly cleaned with distilled water to wash away soil particles sticking to the plant samples. Roots and internodes were sliced into about 0.5-cm pieces and disinfected for 2-3 min with 1% sodium hypochlorite. These segments were then washed three times, for 2-3 min every time, with sterile distilled water and dried on sterile filter paper. Ten disinfected pieces were placed in each 9-cm-diameter Petri dish containing potato dextrose agar (PDA) to which amoxicillin was added to inhibit bacterial contamination. The plates were placed in an incubator at 24°C and the fungal growth was observed.

The fungal colonies that emerged were purified and identified to the species level using the standard taxonomic keys (Domsch et al., 1980; Watanabe, 2002; Barnett and Hunter, 2006). The identification was done on the basis of colony characters, morphology of mycelium, reproductive structures, and morphology of spores. *F. graminearum* was chosen for further pathogenicity testing and field inoculations.

Pathogen selection and inoculum preparation

A purified culture of *F. graminearum* was chosen to use in the field experiment on the basis of its high pathogenicity. Spores were collected from the fungal cultures grown on PDA after sufficient growth and suspended in sterile distilled water. The resultant spore suspension was appropriately adjusted to 1×10^6 spores/mL for the inoculation of seeds and spikes.

Field experiment

The field trial was carried out during the growing season of 2021-2022 in the agricultural fields in the Al-Shirqat district of Salah Al-Din Province, Iraq. The experimental design used was the Randomized Complete Block Design (RCBD) and there were three replications for each treatment. Each plot measured 1 × 1 m. Adana 98 and Wafiya, two wheat cultivars were tested under 10 treatment regimes.

In order to establish the pathogen, seeds for the infected treatments were treated with *F. graminearum* inoculum while the seeds for the healthy control were treated with sterile water only. The seeds were then planted in the labeled micro plots and watered to promote germination and establishment of seedlings.

Using the cotton wool inoculation method, spikes were inoculated at the flowering and early heading stages with a spore suspension of *F. graminearum* at 1×10^6 spores/mL. A cotton wool swab soaked in the spore suspension was applied to the central spikelet of each selected spike. Sterile distilled water was used to moisten the cotton wool for the control treatment. The inoculations of spikes were repeated during the 10-day period. Furthermore, the same spore suspension was applied to the spikes at the rate of 5 mL/replicate and sterile distilled water was applied to all the corresponding controls.

Experimental treatments

The experiment was conducted with two wheat cultivars (Adana 98 and Wafiya) and the following ten treatments:

T1 = Healthy control (Seeds treated with water only),

T2 = Infected control (*F. graminearum* inoculation only),

T3 = *F. graminearum* inoculation + Gibberellin,

T4 = *F. graminearum* inoculation + Nano-Zn,

T5 = *F. graminearum* inoculation + Fungicide (Tebuconazole),

T6 = *F. graminearum* inoculation + SA,

T7 = *F. graminearum* inoculation + Tebuconazole + Nano-Zn,

T8 = *F. graminearum* inoculation + Tebuconazole + Gibberellin,

T9 = *F. graminearum* inoculation + Tebuconazole + SA and

T10 = *F. graminearum* inoculation + Tebuconazole + Nano-Zn + Gibberellin

The efficacy of the treatments was assessed on each of the two cultivars individually.

Measurement of agronomic and growth traits

The following growth and yield parameters were evaluated:

Plant height (cm)

Plant height was recorded from soil level to the tip of the spike excluding awns at full flowering stage. Five representative main tillers per plot were measured and the mean value calculated.

Flag leaf area (cm^2)

The area of flag leaves was determined by measuring 5 representative flag leaves per plot according to the formula used by Thomas (1975):

Leaf area = length × width (midpoint) × 0.95

The average of the leaf area was determined for each plot.

Root length (cm)

Five plants at random were carefully removed from each plot and the length of each root system was measured from the root–shoot junction to the tip of the longest root. The average value of root length was determined for each plot.

Fresh vegetative weight (g)

Five plants were removed from each plot and the fresh vegetative biomass of these plants was instantly measured with a sensitive balance. The results were expressed in 'g' per five plants and converted to 'g' per plant.

Dry weight (g/plant)

The above-ground parts of the sampled plants were dried in the oven to a constant weight. Dry biomass was measured and expressed in g/plant.

100-grain weight (g)

The weight of 100 grains from each plot was taken on a sensitive analytical balance and the weight was recorded in 'g'.

Statistical analysis

The experimental data were analyzed by analysis of variance (ANOVA) suitable for the randomized complete block design to determine the effects of cultivars, treatments and their interaction. The Duncan's multiple range test was used for comparison of treatment means at 5% level of significance ($P < 0.05$). The plot was used as the experimental unit and measurements taken on individual plants within a plot were treated as subsamples.

Results and Discussion

Plant height

The data in Table 1 showed that the height of plants was the maximum (88.5 cm) in Treatment 10 (tebuconazole + Zn + gibberellin), while the infected control (Treatment 2) showed the lowest plant height of 68.0 cm. The increased plant height in Treatment 10 might have been due to the cumulative results of disease control by tebuconazole, enhanced plant physiological performance by the application of zinc and improved cell division and elongation caused by gibberellins. Tebuconazole belongs to triazole group of fungicides that inhibits the formation of ergosterol causing disruption of fungal membrane integrity and inhibiting mycelial growth of fungi (Palazzini et al., 2018). Unlike gibberellins which stimulate shoot growth by promoting cell division and elongation, zinc stimulates vegetative growth, such as increase in plant height and leaf area (Al-Tamimi and Al-Watif, 2015). The decrease in plant height in the infected control might have been related to the inhibitory effect of fungal phytotoxins and cell wall-degrading enzymes which negatively affected plant growth and tissue integrity (Paper et al., 2010; Horevaji et al., 2012). As far as cultivar performance was concerned, the plant height of Wafiya (83.0 cm) was more than that of Adana 98 (74.3 cm) indicating differences in plant growth traits and reaction to FHB.

Root length

Table 2 indicates that the longest roots (12.5 cm) were found in Treatment 10 while the shortest roots (5.5 cm) were recorded in the infected control (Treatment 2). The higher root length for the Treatment 10 could have been due to the synergistic effects of disease suppression due to tebuconazole, enhanced physiologic activity due to zinc and growth regulation by gibberellin. Triazole fungicides have been reported to lead to decreased severity of FHB coupled with lower DON levels which may have a positive impact on plant performance under disease pressure (Palazzini et al., 2018). Involvement of Zinc in tryptophan metabolism is associated with the biosynthesis of auxin which helps in root development (Mora et al., 2012; Al-Dulaimi and Henshal, 2017). Gibberellins also have an effect on root elongation by interacting with the growth processes mediated by auxin (Abdul, 1987). The shorter roots in infected control plants, however, might have been caused by root damage by the pathogen, decreased ability to absorb water and nutrients, and production of fungal toxins (Smiley et al., 2005; Masuda et al., 2007). Regarding cultivars, Wafiya plants produced longer roots (9.5 cm) than Adana 98 (8.6 cm).

Leaf area

Table 3 shows that the infected control had the smallest leaf area of 13.3 m^2 while the highest value of leaf area (21.5 m^2) was obtained in the Treatment 10 (tebuconazole + Zn + gibberellin). The better performance of treatment 10 might be linked with the synergistic action of disease control, better zinc nutrition and gibberellin induced leaf expansion. Tebuconazole prevents fungus growth by inhibiting the biosynthesis of sterols, which can ultimately result in a decrease in the damage caused by the fungus to the tissues of the plant (Ghathwan, 2022). Zinc is involved in the photosynthetic processes and enzymatic activities and stimulates production of assimilates and leaf development (Al-Tamimi and Al-Watif, 2015). Gibberellins also stimulate cell growth and can lead to greater leaf area (Ashraf et al., 2002; Al-Habiti et al., 2017). On the other hand, the decrease in leaf area of the infected control could have been due to disease damage, the inability of the roots to function, and disruptions in nutrient absorption (Paulitz et al., 2002). In addition, cultivar Wafiya had a larger leaf area than cultivar Adana 98 (19.6 and 17.7 m^2, respectively).

Table 1. Effect of treatments on plant height (cm).

Cultivar	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	Cultivar mean
Adana 98	83 c	70 hi	73 gf	68 ij	67 j	72 gh	76 e	73 gf	79 d	82 c	74.3 B
Wafiya	75 ef	66 j	87 b	87 b	87 b	87 b	98 a	86 b	82 c	75 ef	83 A
Treatment mean	79 CB	68 E	80 CB	78 D	77 D	79.5 CB	87 A	79.5 CB	80.5 B	88.5 CD	-

T1 = Healthy control (Seeds treated with water only), T2 = Infected control (*F. graminearum* inoculation only), T3 = *F. graminearum* inoculation + Gibberellin, T4 = *F. graminearum* inoculation + Nano-Zn, T5 = *F. graminearum* inoculation + Fungicide (Tebuconazole), T6 = *F. graminearum* inoculation + SA, T7 = *F. graminearum* Inoculation + Tebuconazole + Nano-Zn, T8 = *F. graminearum* inoculation + Tebuconazole + Gibberellin, T9 = *F. graminearum* inoculation + Tebuconazole + SA, and T10 = *F. graminearum* inoculation + Tebuconazole + Nano-Zn + Gibberellin.
Means with the same letters are not significantly different (P ≤ 0.05).

Table 2. Effect of treatments on root length (cm).

Cultivar	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	Cultivar mean
Adana 98	9 ed	5 h	7 gf	7 gf	10 cd	8 ef	9 ed	10 cd	7 gf	14 a	8.6 B
Wafiya	12 b	6 g	9 ed	9 ed	8 ef	10 cd	11 d	10 cd	7 gf	11 c	9.5 A
Treatment mean	10.5 B	5.5 G	8 E	8 E	9 D	9 D	10 D	10 C	7 F	12.5 A	-

T1 = Healthy control (Seeds treated with water only), T2 = Infected control (*F. graminearum* inoculation only), T3 = *F. graminearum* inoculation + Gibberellin, T4 = *F. graminearum* inoculation + Nano-Zn, T5 = *F. graminearum* inoculation + Fungicide (Tebuconazole), T6 = *F. graminearum* inoculation + SA, T7 = *F. graminearum* Inoculation + Tebuconazole + Nano-Zn, T8 = *F. graminearum* inoculation + Tebuconazole + Gibberellin, T9 = *F. graminearum* inoculation + Tebuconazole + SA, and T10 = *F. graminearum* inoculation + Tebuconazole + Nano-Zn + Gibberellin.
Means with the same letters are not significantly different (P ≤ 0.05).

Table 3. Effect of treatments on leaf area (m^2).

Cultivar	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	Cultivar mean
Adana 98	20 cde	13.3 i	17 g	19 cde	15 h	19 ef	18 fg	18 fg	17 g	21 cde	17.7 B
Wafiya	19 ef	13.3 i	18 fg	18 bcd	22 b	21 bc	24 a	20 cde	19 ef	22 def	19.6 A
Treatment mean	19.5	13.3 G	17.5 F	18.5	18.5	20 ABC	21 A	19 CDE	18 EF	21.5	-

T1 = Healthy control (Seeds treated with water only), T2 = Infected control (*F. graminearum* inoculation only), T3 = *F. graminearum* inoculation + Gibberellin, T4 = *F. graminearum* inoculation + Nano-Zn, T5 = *F. graminearum* inoculation + Fungicide (Tebuconazole), T6 = *F. graminearum* inoculation + SA, T7 = *F. graminearum* Inoculation + Tebuconazole + Nano-Zn, T8 = *F. graminearum* inoculation + Tebuconazole + Gibberellin, T9 = *F. graminearum* inoculation + Tebuconazole + SA, and T10 = *F. graminearum* inoculation + Tebuconazole + Nano-Zn + Gibberellin.
Means with the same letters are not significantly different (P ≤ 0.05).

Fresh vegetative weight

The results in Table 4 revealed that Treatment 6 (*F. graminearum* inoculation + SA) produced the highest fresh vegetative weight of 40.0 g while infected control produced the lowest fresh vegetative weight of 20.5 g. The increased fresh weight in the plants treated with salicylic acid could be related to its role in controlling plant defense responses, antioxidant activity and physiological processes involved in plant stress, aiding in the maintenance of plant growth under pathogen stress (Azooz, 2009; Al-Jubouri and Hassan, 2017). Salicylic acid has also been found to have an inhibitory effect on the growth of *F. graminearum* and affect mycotoxin production under certain experimental conditions (Qi et al., 2012; Al-Jubouri and Hassan, 2021). On the other hand, the lower fresh weight observed in the infected control could have been a result of tissue damage and/or a disruption in the normal growth of the plant caused by the disease. Fungal cell wall degrading enzymes such as pectinases can also play a role in the

degradation of host tissue (Kikot et al., 2008). As regards cultivars, Wafiya had more fresh vegetative weight of 34.8 g than Adana 98 which gave 29.8 g of fresh weight.

Dry weight

Table 5 indicated that dry weight was the highest (22.5 g) in Treatment 7 (tebuconazole + nano-zinc) while the infected control had the lowest dry weight of 11.5 g. The improvement in plant physiological functions coupled with the disease suppression brought about by tebuconazole under Treatment 7 might have contributed to the increased dry matter accumulation. Systemic triazole fungicides such as tebuconazole have been applied to control fungal diseases, including those incited by different species of *Fusarium* (Bayer, 2000). Zinc has been found to be involved in key metabolic and enzymatic functions that are vital for plant growth and dry matter production (Al-Habiti et al., 2017). The lower dry weight of the infected control might have been due to deleterious effects of pathogen infection and associated toxic compound(s) on plant growth and biomass accumulation (Ibrahim, 2018). Likewise, the dry weight of cultivar Wafiya was slightly higher than that of Adana 98 giving dry weights of 17.9 g and 17.4 g, respectively.

100-Grain weight

The 100-grain weight for different treatments showed that Treatment 8 (tebuconazole + gibberellin) had the highest 100-grain weight of 5.75 g while the infected control had the lowest value of 4.0 g as shown in Table 6. The increased grain weight with Treatment 8 might have been related to reduced disease pressure after fungicide treatment and possibly to gibberellin in regard to assimilates allocation and grain development. Effective disease management may help preserve photosynthetically active tissues and sustain assimilate supply during grain filling, while gibberellins control several developmental processes involved in plant growth and reproductive development (Gallant, 2004). Conversely, the lower 100-grain weight in the infected control might have been associated with FHB-induced disruptions in grain development and the accumulation of mycotoxins, including trichothecenes. FHB results in grain bleaching, shriveling, and poor grain quality whereas DON contamination can impact grain safety (Oldenburg, 2004; Shah et al., 2018; Sarowar et al., 2019). However, there was no significant difference between the 100-grain weight of Wafiya and Adana 98, which were 5.10 g and 4.95 g respectively.

Table 4. Effect of treatments on fresh vegetative weight (g).

Cultivar	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	Cultivar mean
Adana 98	44 abc	21 g	33 defg	25 bcde	25 efg	30 efg	34 abcd	28 cde	25 efg	33	29.8 B
Wafiya	40 ab	20 fg	28 de	37 defg	30 efg	50 a	41	35 def	30 efg	37	34.8 A
Treatment mean	42 A	20.5 F	30.5 DE	31 CDE	27.5 E	40 A	37.5	31.5	27.5 E	35 BCD	-

T1 = Healthy control (Seeds treated with water only), T2 = Infected control (*F. graminearum* inoculation only), T3 = *F. graminearum* inoculation + Gibberellin, T4 = *F. graminearum* inoculation + Nano-Zn, T5 = *F. graminearum* inoculation + Fungicide (Tebuconazole), T6 = *F. graminearum* inoculation + SA, T7 = *F. graminearum* Inoculation + Tebuconazole + Nano-Zn, T8 = *F. graminearum* inoculation + Tebuconazole + Gibberellin, T9 = *F. graminearum* inoculation + Tebuconazole + SA, and T10 = *F. graminearum* inoculation + Tebuconazole + Nano-Zn + Gibberellin.

Means with the same letters are not significantly different ($P \leq 0.05$).

Table 5. Effect of treatments on dry weight (g).

Cultivar	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	Cultivar mean
Adana 98	20 e	12 m	14 k	18 g	15 j	25 i	22 c	17 h	13 l	18 g	17.4 B
Wafiya	22 c	11 n	21 d	13 l	16 i	17 h	23 b	19 f	20 e	17 h	17.9 A
Treatment mean	21 B	11.5 G	17.5 D	15.5 F	15.5 F	21 B	22.5 A	18 C	16.5 E	17.5 D	-

T1 = Healthy control (Seeds treated with water only), T2 = Infected control (*F. graminearum* inoculation only), T3 = *F. graminearum* inoculation + Gibberellin, T4 = *F. graminearum* inoculation + Nano-Zn, T5 = *F. graminearum* inoculation + Fungicide (Tebuconazole), T6 = *F. graminearum* inoculation + SA, T7 = *F. graminearum* Inoculation + Tebuconazole + Nano-Zn, T8 = *F. graminearum* inoculation + Tebuconazole + Gibberellin, T9 = *F. graminearum* inoculation + Tebuconazole + SA, and T10 = *F. graminearum* inoculation + Tebuconazole + Nano-Zn + Gibberellin.

Means with the same letters are not significantly different ($P \leq 0.05$).

Table 6. Effect of treatments on 100-grain weight (g).

Cultivar	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	Cultivar mean
Adana 98	5.6 ab	4 fg	6 a	4 fg	5 bc	5.7 ab	3.8 g	5.6 ab	5.4 bc	4.4 ef	4.95 A
Wafiya	4.5 e	4 fg	5 cd	4.7 de	6 a	5 bc	4.9 d	5.9 a	5.3 bc	5.7 ab	5.1 A
Treatment mean	5.05 C	4 E	5.5 AB	4.35 D	5.5 AB	5.35 Ab	4.35 D	5.75 A	5.35 B	5.05 C	-

T1 = Healthy control (Seeds treated with water only), T2 = Infected control (*F. graminearum* inoculation only), T3 = *F. graminearum* inoculation + Gibberellin, T4 = *F. graminearum* inoculation + Nano-Zn, T5 = *F. graminearum* inoculation + Fungicide (Tebuconazole), T6 = *F. graminearum* inoculation + SA, T7 = *F. graminearum* Inoculation + Tebuconazole + Nano-Zn, T8 = *F. graminearum* inoculation + Tebuconazole + Gibberellin, T9 = *F. graminearum* inoculation + Tebuconazole + SA, and T10 = *F. graminearum* inoculation + Tebuconazole + Nano-Zn + Gibberellin.
Means with the same letters are not significantly different (P ≤ 0.05).

Authors' Contributions

ZKRM and KAM conceptualized and designed the experiment. ZKRM conducted the experimental work. AMA and AAAA provided overall supervision and ensured methodological rigor and analytical consistency throughout the study. BDA provided critical guidance on experimental design, data interpretation, and research refinement at various stages. ZKRM, KAM, and AAAA contributed to drafting the initial manuscript, organizing the content, compiling the results, and developing preliminary interpretations. All authors critically reviewed the manuscript, contributed to its intellectual refinement, verified the data and analyses, and approved the final version for submission.

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Conflict of Interest

The authors declare no conflict of interest.

Sustainable Development Goals Targeted

SDG 2: Zero Hunger
SDG 3: Good Health and Well-being
SDG 12: Responsible Consumption and Production

Policy Addressed

The findings support further evaluation of integrated Fusarium head blight (FHB) management strategies within sustainable wheat production programmes. However, field-level recommendations require validation of disease severity, grain yield, mycotoxin contamination, treatment economics, environmental safety, and long-term effectiveness under diverse agroecological conditions.

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