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Fertigation of wheat (*Triticum aestivum* L.) cultivars with zinc leads to enhanced yield and marginal rate of return in silty loamy soils

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ABSTRACT

This study was aimed to understand the role of Zn fertilizer ($ZnSO_4 \cdot 7H_2O$) applied through soil media, foliar spray and in combination for enhancing yield and marginal rate of return of wheat crop in filed conditions. Four wheat cultivars; Anaj-2017; Akbaer-2019; FSD-2008 and Zincol-2016 were sown in randomized complete block design in field. The Zn fertilizer was applied as soil media, foliar spray and in combination of soil + foliar media. A significant enhancement in plant height (18.2 %), leaf area index (28 %), heat unit efficiency (25.1 %) and SPAD (23 %) value was observed in wheat cultivars with Zn fertilization. However, the impact of soil + foliar media (T4) Zn application (15 kg $ZnSO_4$ ha^{-1} (soil) + 1 % $ZnSO_4$ foliar spray solution) was higher than soil media or foliar spray. The protein, ash, fat and phytate contents were enhanced to 13.38 %, 2 %, 0.57 % and 27 % respectively while significant decrease in α-amylase (−29 %) and was recorded after Zn fertilization. At T4 considerable enhancement in grain yield (4.2 tons ha^{-1}), harvest index (55.3 %), internal use efficiency and partial nutrient budget was recorded. It was observed that uptake K, N, Zn and Fe were enhanced while that of P were reduced after Zn fertigation especially at T4 in wheat cultivars. The value cost ratio (VCR) and marginal rate of return (MRR) to farmers was better at T4 as compared to T1-T3 in all wheat cultivars. Finally, Zn applied as soil + foliar spray was most effect while among cultivars Zincol-2016 and Akbar-2019 showed more yield potential than Anaj-2017 and FSD-2008. It has been established that the soil–plant-mineral nutrition nexus is the road leading to fetching higher income, sequestration of carbon dioxide from the air and also ensuring food and nutrition security.

1. Introduction

Food security has been a longstanding concern for humanity since time immemorial to date. However, since the start of 21st century climate change, soilage of water and soil resources and reduction in yield of agricultural crops are the consistent threats to human existence. So, it is the need of time to ensure food security in order to eliminate hunger and pandemic malnutrition across the globe. The United National Sustainable Development Goals (SDGs-2015) were devised to eliminate hunger from the word by 2050 (Fanzo et al., 2020). However, there are many hurdles in attaining these goals, amongst decrease in soil fertility is of main concern (Alloway, 2009).

The nutrient deficient soils are the main cause of reduction in crop yield of economically important crops. As adequate supply of soil micro- and macro-nutrients are required for proper physiological and biochemical activities by plants (Noreen et al., 2018). Although Zn is required in limited quantity, its absence adversely impacts the development and efficiency of plants. Since Zn can't be subbed by some other metal particle for completing physiological and biochemical activities in plant's cellular system (Bänziger and Long, 2000, Noreen et al., 2023), therefore its adequate supply in the soils is essential for optimal growth of the plants. While on the other hand, Zn deficiency in common nutrient chaos in soils of many countries including Pakistan that ultimatly results in reduction in productivity of crops as well as nutritional value of the

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crops. The soils are deficient in Zn followed by Fe, B, Mo, Cu and Mn minerals. The extent of Zn deficiency is 87 %, 37 %, 47 % and 90 % in soils of Punjab, Khyber Pakhtunkhwa, Sindh and Balochistan provinces, respectively (Zia et al., 2006). In wheat, grain and seed production was affected negatively to a greater proportion in comparison with total dry matter yield due to Zn deficiency. The critical deficiency concentration was below 15–20 mg Zn kg^{-1}. This was due to impairment of pollen fertility development during reproductive stage (Cakmak, 2008b).

The Zn deficiency limits the net photosynthetic rate, inhibits RNA synthesis, and restricts growth and development leading to showing of the chlorosis in the interveinal area. Zn absorbed through roots was well distributed among leaves, stems and roots, while foliar droplets moved primarily towards expanding leaf tips and showing a little flow towards the older organs (Huang et al., 2000, Thiébaut and Hanikenne, 2022). The plants did not have the ability to store up Zn for its later movement towards the growing plants, when it was needed during growth and development (Smith et al., 2021). There are evidences that micronutrient contents in wheat grains have been reduced to half i.e. Zn (–33–35 %), iron and copper (−39 %), as recorded between 1843–1960, for example prior to the presentation of high yielding cultivars, from that point, a sharp decrease in Zn, Fe, Cu, I and Se was seen after 1960 s. the grain crops are normally low in Zn contents and this problems is more terrible in Zn-deficient soils (Fan et al., 2016).

Wheat is the main staple dietary food of billions of humans on earth. It is the need of time that wheat grains may not only provide sufficient number of calories to meet physiological necessities but additionally be stacked with higher fundamental dietary supplements (Torun et al., 2000). The agronomic biofortification is considered a “shotgun” way to deal with right the lack of Zn components either through application in the soil as well as through foliage taking during the vegetative and reproductive stages (Cakmak, 2008a). In this regard, this study was aimed to understand the role of Zn fertilizer application as foliar and soil media in enhancing growth, grain yield and marginal rate of return of wheat crop in filed conditions.

2. Materials and Methods

2.1. Experimental details

Four local wheat cultivars *viz*. Akbar-2016, Zincol-2016, Anaj- 2017 and FSD-2008 were selected from AARI. An experiment was designed on field conditions at Experimental Research Station, Department of Soil Science, Bahauddin Zakariya University, Multan-Pakistan. Experimental field area, was divided into four plots, with a size of 5.0 m^2. Each plot was sub divided into four sub-plots having 4 cultivars and 4 fertilizer levels, totaling 16 sub-plots (Fig. S4). The seeds were sown using hand-drill by keeping the line distance of 25 cm from one another with uniform seed wight of 25 kg ha^{-1} for each cultivar.

Soil and irrigation water samples were analyzed before cultivation (Tables S1-S3). Before planting, the seeds were treated with fungicide, Thiophanate-methyl-70 % WP (3 g kg^{-1} seed weight) as a preventive measure to control contagious fungicides on seed surface. The $ZnSO_4 \cdot 7H_2O$ was used as the source of Zn to be used in three different modes; T1 = control (water spray only); T2 = 15 kg Zn $SO_4 \cdot 7H_2O$ ha^{-1} (added manually in soil before sowing), T3 = foliar spray of 1 % Zn $SO_4 \cdot 7H_2O$ solution at tillering (0.5 %) and anthesis (0.5 %) @ 600 L ha^{-1} foliar spray and T4 = 15 kg Zn $SO_4 \cdot 7H_2O$ ha^{-1} (added manually in soil before sowing) + foliar spray of 1 % Zn $SO_4 \cdot 7H_2O$ solution at tillering (0.5 %) and anthesis (0.5 %) @ 600 L ha^{-1} foliar spray. Basal fertilizer doses were used at the rate of 120 kg ha^{-1}N (urea, 46 % N); 80 kg P_2O_5 ha^{-1} (TSP, 46 % P_2O_5) and 60 kg K_2O ha^{-1} (Sulphate of potash).

2.2. Measurements

Plant height was recorded at the time of maturity while and leaf area index was estimated from mature leaves of five plants by procedures of Amanullah et al. (2009) and Ahmad et al. (2015). Heat-use productivity (HUE) [kg ha^{-1} °C/day] was worked out according to Nandini and Sridhara, (2019).

2.3. Gas exchange attributes

The gas exchange characteristics were recorded utilizing Infrared Gas Analyzer (IRGA) [LCI-Framework, ADC-Bioscientific Ltd., Hoddesdon, UK]. The flag leaves were enclosed in an assimilation chamber and gas exchange parameters were recorded in data logger in about 2 min, when no noticeable changes in leaf respiration were registered. Under atmospheric CO_2 and ambient light conditions, data on photosynthesis were recorded at 09:00 to 10:00 a.m under a clear sky and saturating light conduction.

2.4. Grain yield and its components

The wheat crop was harvested at its physiological maturity stage (when the green color from the glumes and kernels had disappeared completely) during 2nd week of April. The grain yield and its determinants were quantified. The central rows were harvested manually, bundled, sundried *in-situ* and total biological yield was recorded. The different parameter for grain yield was also measured according to Islam et al. (2017).

2.5. Harvest index

The harvest index refers to crop simulation model that accounts to the fraction of the total aboveground biomass allocated to the grain portion. It was enumerated according to formula of Kemanian et al. (2007).

$$Harvestindex(\%) = \frac{Totalgrainyiled(tha-1)}{Totalbiomass(tha-1)} \times 100$$

2.6. Ionic constituents

The Ryan et al. (2001) technique was employed to estimate ionic constituents (K, Zn, Fe) from oven dried grains by Flame Photometer (PFP Jenway Staffardshire, U.K). The N concentration was determined by Kjeldahl method Bradstreet (1954) and P by colorimetry (ammonium vanadate-ammonium molybdate, yellow color method (Allen, 1940). The material was digested by using digestion mixture [nitric acid-perchloric acid (HNO_3 – $HClO_4$, 2:1 ratio)].

2.7. Nutritional analysis

The grain protein, fat and ash contents according to the methodology of Rehman et al. (2020). The α-amylase was determined by Bernfeld (1951), while phytate contents were assayed by Haug and Lantzsch (1983) methodology.

2.8. Nutrient-use-efficiency

The nutrient-use-efficiency parameters including partial factor productivity (PFP); internal use efficiency (IUE); partial nutrient budget (PNB); agronomic efficiency (AE), apparent recovery efficiency (ARE) and physiological efficiency (PE) were estimated by Rawal et al. (2022) equations.

2.9. Economic analysis

The nutrient economic analysis Zn fertilization on wheat cultivars was worked out (Program, 1988), while economic metrics, i.e., marginal rate of return (MRR), net present worth (NPW) and value cost ratio (VCR) were computed according to Sarkar et al. (2018). The mean wheat grain yield data were adjusted down by 12.5 % in order to narrow the possible yield gap that might had happened due to differences in field management and experimental grain yield. The costs incurred in farm inputs and wheat grains harvested were calculated on hectare basis in Pakistan rupees (PKR ha^{-1}). The MRR determines the returns per unit of investment in fertilizer between a pair of treatments and expressed as a percentage.

2.10. Statistical analysis

The experimental work was in Randomized Complete Block Design. Each experimental unit was repeated four time. CoStat (6.311) a computer-based software was used for statistical analysis. The main effects were compared using the least significance difference (LSD) test at 0.05 level of probability.

3. Results

3.1. Plant height and leaf area index (LAI)

The results revealed that plant height and LAI were significantly affected by Zn fertilization. However, more pronounced increase in these parameters was observed at T4 as compared to T1-T3. Among cultivars, Akbar-2019 and Zincol-2016 were more responsive to plant height with an increase of 18.0 % and 18.2 % respectively at T4 as compared to Anaj-2017 and FSD-2008 which exhibited 15.3 % and 10.9 % enhancement respectively (Fig. 1). Similarly, Anaj-2017 followed by Zincol-2016, Akbar-2019 and FSD-2008 resulted in 28 %, 20.4 %, 16.1 % and 11.9 % respectively increase in LAI at T4 over T1 (Fig. 1).

3.2. Heat unit efficiency (HUE) and SPAD

Zn fertilization has a positive effect on HUE and SPAD values. HUE was more significantly improved to 8.1 % (Akbar-2019), 14.7 % (Akbar-2019) and 25.1 % (Zincol-2016) at T2, T3 and T4 respectively. While, amongst wheat cultivars maximum enhancement in SPAD at T2 (8 %), T3 (14 %) and T4 (23 %) was observed in Zincol-2016. Zincol-2016 and Akbar-2019 were more responsive to Zn treatments in terms of HUE and SPAD (Fig. 1).

3.3. Gas exchange attributes

Data for transpiration rate (*E*), stomatal conductance (*gS*), sub-stomatal conductance (*Ci*) and net photosynthetic rate (*A*) showed significant response to Zn fertilization (Fig. 2). Among treatments T4 showed maximum enhancement up to 38 %, 38.4 %, 32.8 % and 26.6 % in *Ci*, *gS*, *A*, and *E* respectively. However, among cultivars better response of Zn fertilization with respect to *Ci* and *A* was observed in FSD-2008; *gS* in Zincol-2016 and *E* in Akbar-2019 (Fig. 2).

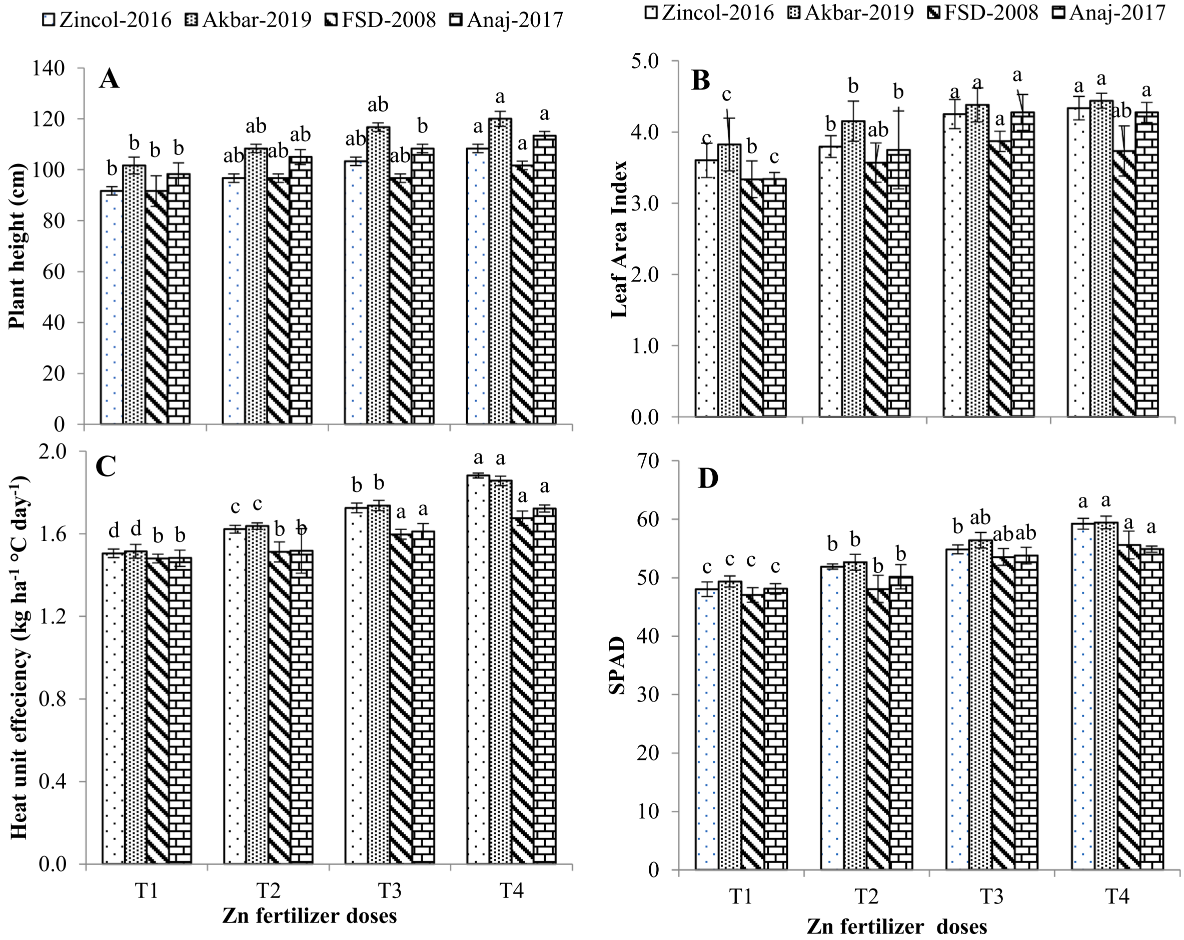


Fig. 1. (A) Plant height (cm); (B) leaf area index; (c) heat unit efficiency (Kg ha^{-1} °C^{-1} day) and SPAD value of wheat cultivars fertigated with Zn fertilizer. T1 = control (water spray); T2 = 15kg$ZnSO_4 \cdot 7H_2O$ ha^{-1}; T3 = Foliar application of $ZnSO_4 \cdot 7H_2O$ solution 1 % (0.5 %+0.5 %) at tillering and anthesis stages; T4 = 15kg$ZnSO_4 \cdot 7H_2O$ ha^{-1} (soil applied) + foliar spray of $ZnSO_4 \cdot 7H_2O$ solution 1 % (0.5 %+0.5 %) at tillering and anthesis stages; different letters (a-c) on bars represent significant difference among treatments at $p < 0.05$ (DMRT).

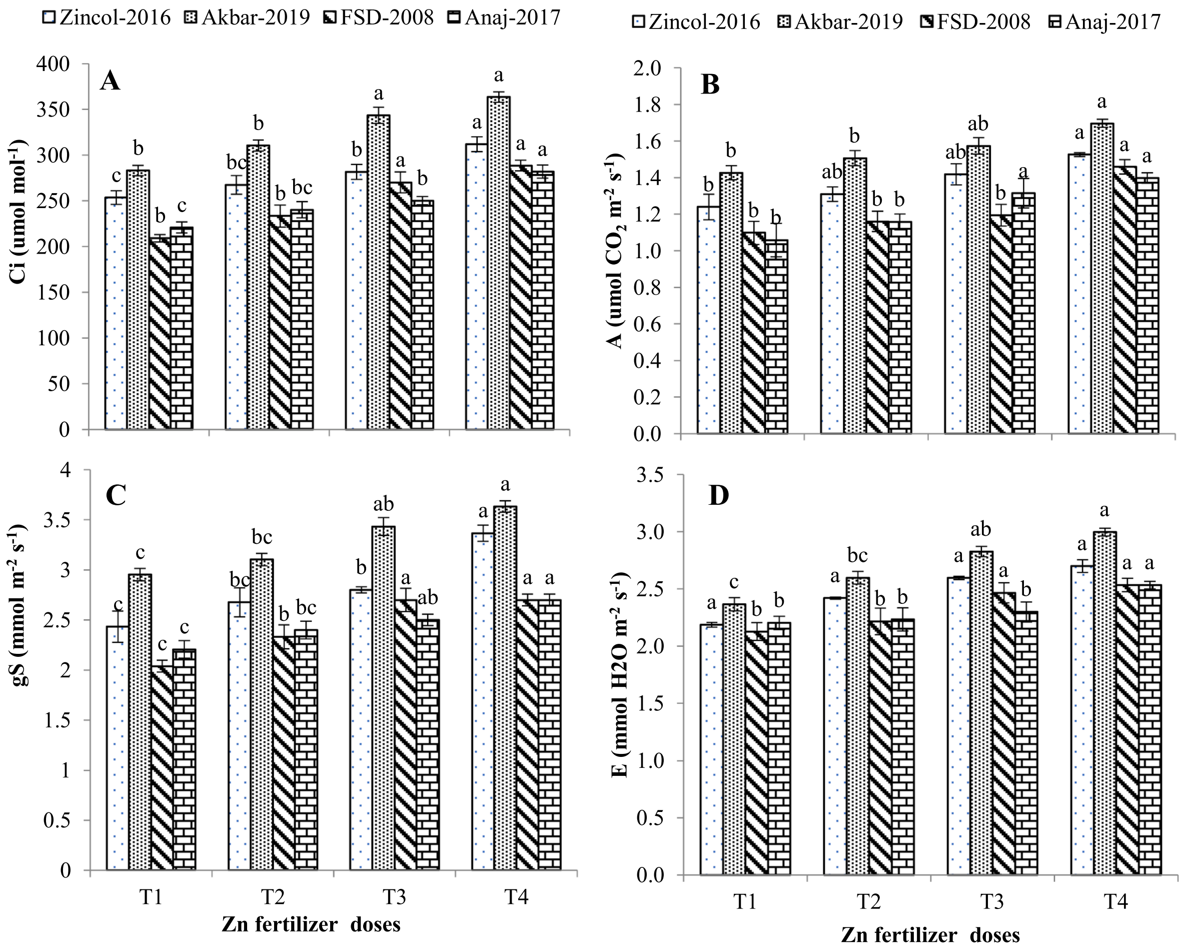


Fig. 2. (A) net photosynthetic rate (*A*); (B) transpiration rate (*E*); (C) stomatal conductance (*gS*) and (D) sub stomatal CO_2 concentration (*Ci*) of wheat cultivars fertigated with Zn fertilizer. Different letters (a-c) on bars represent significant difference among treatments at $p < 0.05$ (DMRT).

3.4. *Yield attributes*

It has been observed that yield attributes showed significant response to Zn fertilization. Among Zn fertilizer treatment (T1-T4) maximum yield, i.e. number of tillers; spike length; grains/spike; thousand grain weight; spikelet/spike and grain yield were gained T4 (Fig. 3). It has been observed that as compared to other cultivars Akbar-2019 produced maximum productive tillers at all Zn fertilizer does, i.e. T1 (295), T2 (300), T3 (307) and T4 (307). Data revealed that higher number of grains spike^{-1} were produced by Akbar-2019 (57, 52, 50 and 47) followed by FSD-2008 (53, 49, 43 and 43), Zincol-2016 (51, 49, 46 and 45) and Anaj-2017 (46, 45, 43 and 40) at T4, T3, T2 and T1 respectively. Maximum 1000 grain weight was observed at T4 in Akbar-2019 (53 g) as compared to Zincol-2016 (46 g), FSD-2008 (44 g) and Anaj-2017 (41 g). With respect to spike length at treatment T4 the maximum length was observed in Akbar-2019 (14 cm) followed by FSD-2008 (13.2 cm), Zincol-2016 (12.4 cm) and Anaj-2017 (12.5 cm). The highest number of spikelets spike^{-1} were recorded in Akbar-2019 (20) as all other cultivars. Similarly, in terms of grain yield cultivars were ranked in order of Akbar-2019 (4.2 tons ha^{-1}) > Zincol-2016 (4.0 tons ha^{-1}) > FSD-2008 (3.8 tons ha^{-1}) > Anaj-2017 (3.8 tons ha^{-1}) at T4 (Fig. 3).

3.5. *Total biological yield and harvest index (HI)*

Zn fertilization caused a significant enhancement in total biological yield and harvest index of all wheat cultivars (Fig. 3). Maximum biological yield (7.8 tons ha^{-1}) was obtained at T4 in Akbar-2019 as compared to other treatments and cultivars. Similarly, highest HI was again maintained by cv. Akbar-2019 at T4 (55.3 %) as compared to T1 (47.1), T2 (49.1) and T3 (52.8 %). The response of wheat cultivars was ranked, Akbar-2019 > FSD-2008 > Zincol-2016 > Anaj-2017 for total biological yield and HI (Fig. 3).

3.6. *Protein fat, ash and phytate contents*

The Zn fertilization caused a significant effect on protein, ash, fat and phytate contents of wheat cultivars (Table 1). Among cultivars Akbar-2019 and Zincol-2016 gathered higher protein contents (13.38 and 12.75Kg Kg^{-1}) respectively as compared FSD-2008 and Anaj-2017 (12.26 and 12.35 Kg Kg^{-1}) respectively at T4. The Abkar-2019 and Zincol-2016 gathered higher fat content (0.57 and 0.47 Kg Kg^{-1}) at T4 as compared to T1 (0.11 Kg Kg^{-1}). The ash contents were also increased from 1.8 Kg Kg^{-1} (T1) to 2.0 Kg Kg^{-1} (T4) in Zincol-2016 and Akbar-2019. Similarly, the phytate contents were also enhanced with Zn fertilization however maximum enhancement of 27 % was observed in Anaj-2017 at T4 (Table 1).

3.7. *α-amylase activity*

Data showed that grain α-amylase activity was significantly affected in response to Zn fertilization and among cultivars (Table 1). The amylase activity was lower gradually with application of Zn fertilizer in all cultivars. Maximum reduction (29 %) in amylase activity was observed in Anaj-2017 at T4. However, at T3 and T2 maximum reduction was 8 % and 2 % respectively in Zincol-2016 (Table 3).

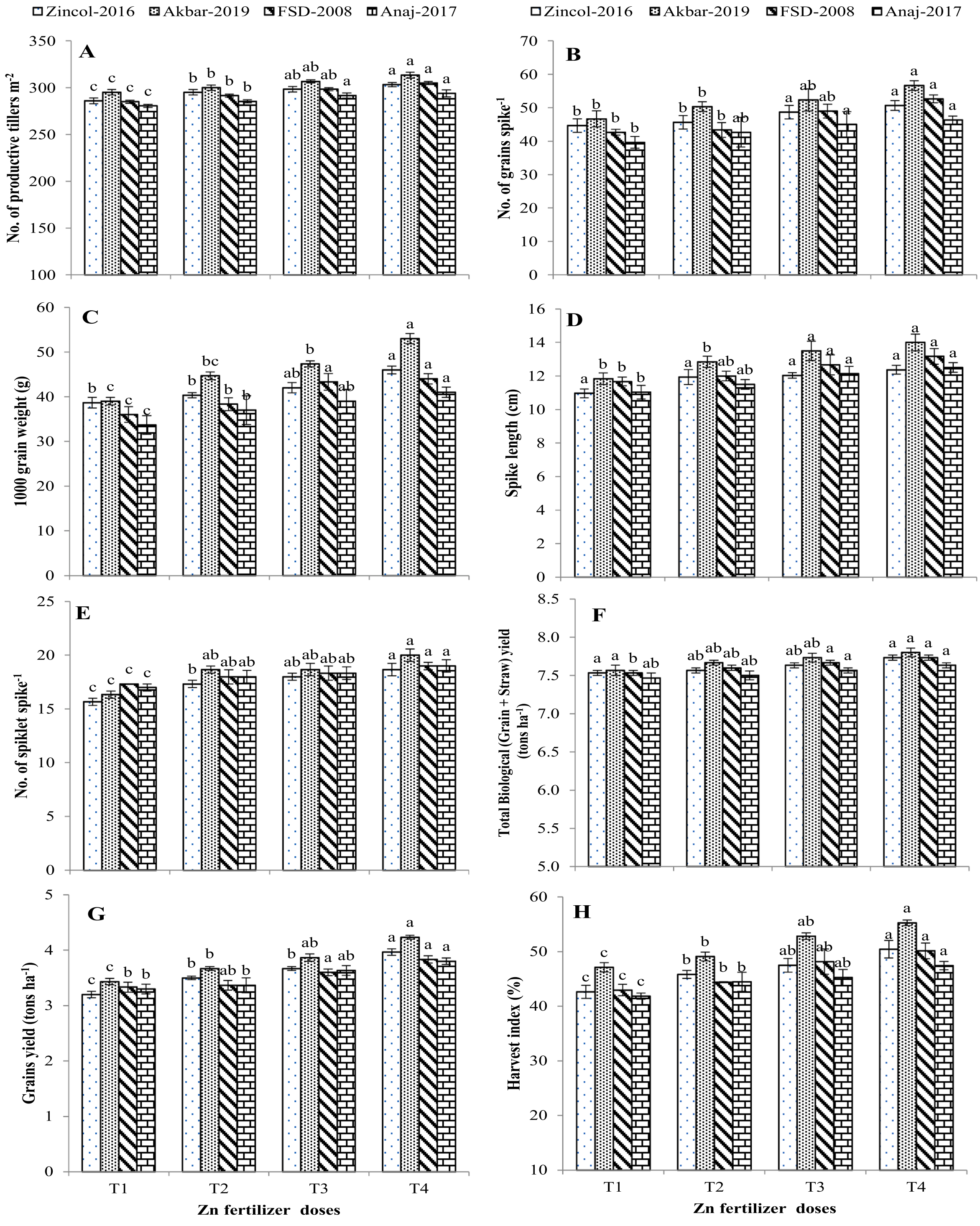


Fig. 3. (A) No. of productive tillers; (B) no. of grains spike^{-1}; (c) 1000 grain weight (g); (d) spike length (cm); (E) number of spikelets spike^{-1}; (F) total biological yield (grain + straw) tons ha^{-1}, (G) grain yield (tons ha^{-1} and (H) harvest index (%) of wheat cultivars fertigated with Zn fertilizer. Different letters (a-c) on bars represent significant difference among treatments at $p < 0.05$ (DMRT).

3.8. Ionic constituents in grains

Zn fertilization caused a significant enhancement in grain nitrogen (N), potassium (K) and zinc (Zn) contents (Table 2). Maximum N concentration of 1.7 % was recorded at T4 (Akbar-2019) followed by 1.65 %, 1.63 % and 1.6 % in Zincol-2016, Anaj-2019 and FSD-2008 respectively at T4. The K contents were increased with Zn fertilization, among cultivars, cvs. Akbar −2019 maintained highest (37 %) increase in K contents at T4 as compared to T2 (12 %) and T3 (23.5 %). Similarly, highest Zn contents (59.7 mg kg^{-1}) were observed in at T4 in Akbar-2019 followed by 56.8 mg kg^{-1} in Zoncol-2016. In response to Zn contents the cultivars were arranged in the order of Akbar-2019 > Zincol-2016 > Anaj-2017 > FSD-2008 (Table 2).

The data revealed that Phosphorus (P) and Iron (Fe) contents were

Table 1
The protein; fat; ash; α-amylase activity and phytic acid content (%) of wheat cultivars fertigated with Zn fertilizer.

Treatments	Cultivars				Mean
	Zincol-2016	Akbar-2019	FSD-2008	Anaj-2017	
Protein contents					
T1	12.28a	12.15b	11.51a	11.52b	11.86a
T2	12.08a	12.75ab	11.63a	11.65ab	12.03a
T3	12.53a	13.23a	11.93a	12.05ab	12.44a
T4	12.75a	13.38a	12.26a	12.35a	12.69a
Replicates: ns, Cultivars: ***, Treatments: ***, Interaction: ***					
Fat contents					
T1	0.11d	0.11d	0.11d	0.10d	0.11d
T2	0.32b	0.36b	0.29b	0.33b	0.33b
T3	0.24c	0.30c	0.26c	0.28c	0.27c
T4	0.47a	0.57a	0.42a	0.424	0.47a
Replicates: ns, Cultivars: ***, Treatments: ***, Interaction: ***					
Ash contents					
T1	1.80a	1.80a	1.41a	1.46a	1.62a
T2	1.81a	1.91a	1.48a	1.52a	1.68a
T3	1.92a	1.94a	1.63a	1.58a	1.77a
T4	2.00a	2.00a	1.67a	1.67a	1.84a
Replicates: ns, Cultivars: ***, Treatments: ***, Interaction: ***					
α-amylase activity					
T1	80.3a	76.2a	81.0a	80.8a	79.6a
T2	78.4ab	69.4b	77.0b	71.9b	74.2a
T3	73.7b	65.4c	72.9c	68.3c	70.1c
T4	71.0c	64.0b	57.4d	60.1d	64.3d
Replicates: ns, Cultivars: ***, Treatments: ***, Interaction: ***					
Phytic acid content					
T1	10.89b	11.15b	10.85b	11.03a	10.98b
T2	11.88ab	11.78ab	12.86a	12.49a	12.25ab
T3	13.14a	12.76a	12.96a	12.29a	12.79a
T4	12.62a	13.02a	13.78a	12.90a	13.08a
Replicates: ns, Cultivars: ***, Treatments: ***, Interaction: ***					

Values are means; letters (a-d) are significant difference among treatments at $p < 0.05$ (DMRT).

reduced with application of Zn fertilizer (T2-T4). The P contents in grains of wheat cultivars were decreased from 24 %, 17 % and 7.5 % at T4, T3 and T2 respectively in Akbar-2019. Similarly, grain Fe contents were also reduced in all wheat cultivars with maximum reduction of 24 % in Akbar-2019 at T4 (Table 2).

3.9. *Zinc nutrient-use efficiency*

Wheat cultivars showed significant response to zinc nutrient use efficiency attributes including partial factor productivity (PFP); internal use efficiency (IUE); partial nutrient budget (PNB); agronomic efficiency (AE), apparent recovery efficiency (ARE) and physiological efficiency (PE) after application of zinc fertilizer (Fig. 4). It has been observed that cuv. Akbar-2019 maintained higher PFP value of 64 kg kg^{-1} at T4. Averaged across Zn doses at T4 the cvs. Zincol-2016 and Akbar-2019 proved to be highly Zn efficient by keeping IUE of 218 and 201 kg kg^{-1} respectively as compared to 186 and 171 kg kg^{-1} by Anaj-2017 and FSD-2008 respectively. In Akbar-2019 the maximum PNB of 0.57 kg kg^{-1} was attained by crop treated at T4 compared to 0.11 kg kg^{-1} T1. Similarly, AE value for Akbar-2019 was of 29.6 kg kg^{-1} was highest at T4 as compared to 10 kg kg^{-1} at T1. The Zn bio-fortified cultivars (Akbar-2019 and Zincol-2016) had better ARE values of 36.5 and 34.2kg kg^{-1} compared to 29.9 to 29.4 kg kg^{-1} by cvs. FSD-2008 and Anaj-2017 respectively at T4. Similarly, averaged across cultivars, maximum PE values of 69 kg kg^{-1} were attained by Akbar-2019 at T4 as compared to 38, 42 and 20 kg kg^{-1} at T3, T2 and T1 (Fig. 4).

Table 2
Effect of different Zn fertilizer on nitrogen (N), phosphorous (P), potassium (K), zinc (Zn) and iron (Fe) contents in grains of four wheat cultivars (Zincol-2016, Akbar-2019, FSD-2008 and Anaj-2017).

Treatments	Zincol-2016	Akbar-2019	FSD-2008	Anaj-2017	Mean
Nitrogen (N)					
T1	1.40c	1.49b	1.40b	1.43b	1.43c
T2	1.50bc	1.59ab	1.47ab	1.49b	1.51bc
T3	1.60ab	1.63a	1.53ab	1.55ab	1.58ab
T4	1.65a	1.70a	1.60a	1.63a	1.65a
Replicates: ns, Cultivars: ***, Treatments: ***, Interaction: **					
Phosphorous (P)					
T1	0.51a	0.53a	0.47a	0.45a	0.49a
T2	0.48a	0.49a	0.44a	0.43a	0.46a
T3	0.43a	0.44a	0.41a	0.40a	0.42a
T4	0.40a	0.40a	0.38a	0.37a	0.39a
Replicates: ns, Cultivars: ***, Treatments: ***, Interaction: **					
Potassium (K)					
T1	0.50b	0.51b	0.49a	0.47b	0.49b
T2	0.56ab	0.57ab	0.53a	0.51ab	0.54ab
T3	0.61ab	0.63ab	0.58a	0.56ab	0.60ab
T4	0.66a	0.70a	0.60a	0.60a	0.64a
Replicates: ns, Cultivars: ***, Treatments: ***, Interaction: **					
Zinc (Zn)					
T1	35.0d	37.0d	29.8d	31.9d	33.43d
T2	41.7c	45.7c	32.8c	36.5c	39.18c
T3	44.4b	50.7b	37.7b	40.0b	43.20b
T4	56.8a	59.7a	40.1a	42.7a	49.82a
Replicates: ns, Cultivars: ***, Treatments: ***, Interaction: **					
Iron (Fe)					
T1	104.8a	108.3a	100.2a	102.3a	103.9a
T2	98.7a	99.2b	97.1b	98.2b	98.3b
T3	96.8a	97.8c	94.2c	95.1c	95.9c
T4	94.3a	82.2d	92.0d	93.0d	93.6d
Replicates: ns, Cultivars: ***, Treatments: ***, Interaction: ***					

Values are means; letters (a-d) are significant difference among treatments at $p < 0.05$ (DMRT).

3.10. *Economic analysis*

The Zn fertilization resulted in higher grain yield which ultimately resulted into better economic yield of wheat cultivars. It has been observed that value cost ratio (VCR) of 4.76:1 was achieved at T4 as compared to 3.95:1 and 3.41:1 at T3 and T2 respectively in cv. Akbar-2019 (Table 3). The marginal rate of return (MRR) was boosted with Zn fertilization (T2-T4) accounting 7-times greater over investment (Table 4). It has also been observed that at T4 net present worth was of PKR 109,700 as compared to PKR 83,600 and 77,100 at T3 and T2 respectively (Table 5).

3.11. *Correlation analysis*

The traits studied after Zn fertilization showed a significant correlation. The pH and HUE were strongly correlated with yield (SL, TGW, NGS, TBY, TGY and HI) and Zn nutrient use efficiency parameters (PE, ARE, AE, PNB, IUE and PFP). Similarly, all Zn nutrient use efficiency parameters were significantly positive correlated with yield attributes (Fig. 5).

4. Discussion

The balanced and precise application of mineral nutrients is a prerequisite and relevant tool to improve productivity of crops, achieving food security and also in relation to promoting sustainable and smart agriculture (Selim, 2021). Among mineral zinc (Zn) has been recognized

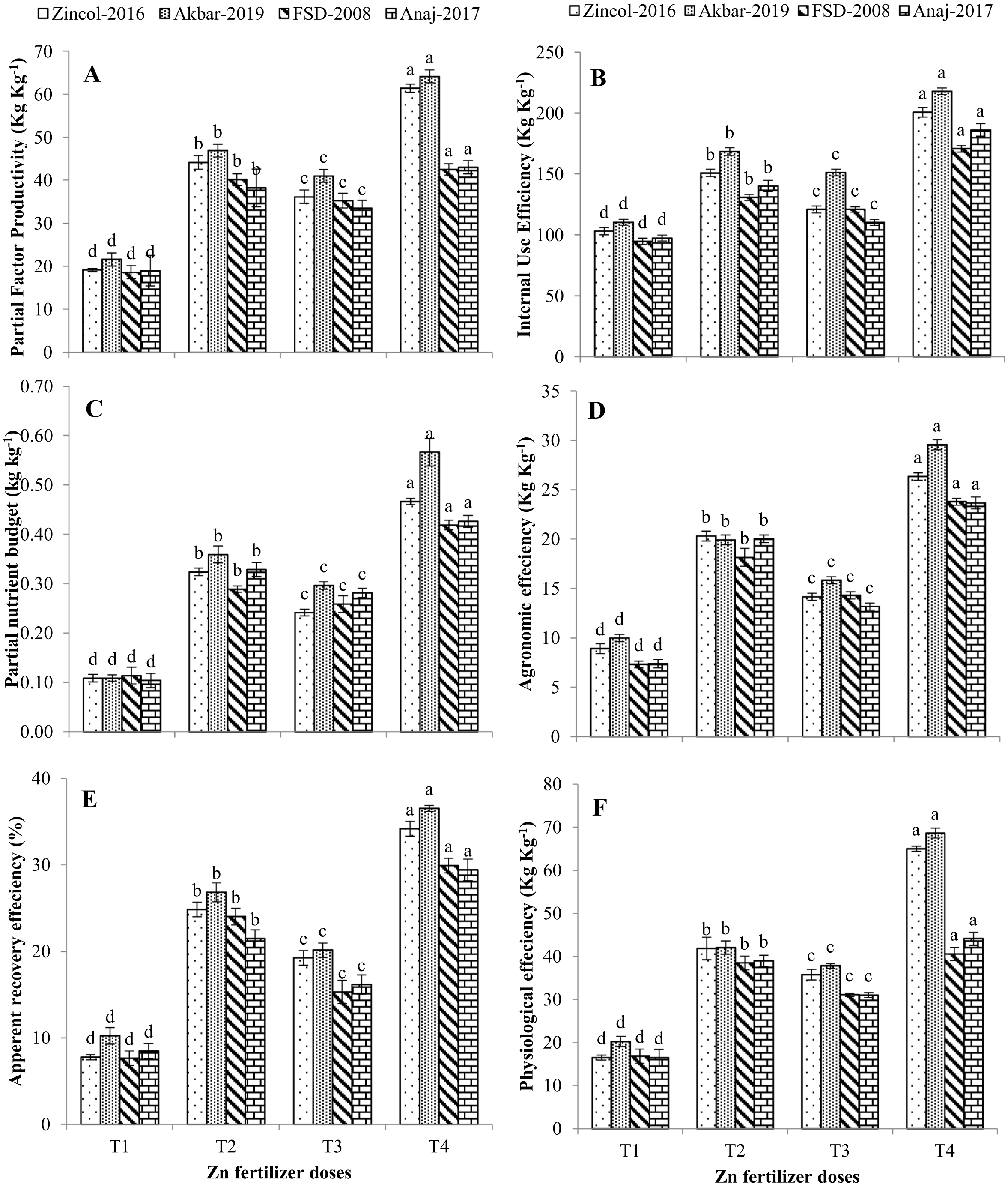


Fig. 4. (A) partial factor productivity; (B) internal use efficiency; (C) partial nutrient budget; (D) agronomic efficiency; (E) apparent recovery efficiency and (F) physiological efficiency of wheat cultivars fertigated with Zn fertilizer. Different letters (a-d) on bars represent significant difference among treatments at $p < 0.05$ (DMRT).

as essential micronutrient that has direct involvement in regulating the uptake and distribution of other essential nutrients for enhance plant growth and yield (Ghani et al., 2022). In this regard, Zn fertigation can potentially enhance growth of plants through improved nutrients up take supplying balanced nutrients supply for enhancing yield (Massoud et al., 2005, Shivay et al., 2014).

The results of this study revealed that application of 15 kg $ZnSO_4$. ha^{-1} in combination to foliar spray of 1 % (0.5 %+0.5 %) $ZnSO_4$ solution at tillering and anthesis stages (T4) enhanced leaf area index (LAI) and plant height of wheat crop when compared to control (T1). Bharti et al. (2014) reported that 20 kg $ZnSO_4$ ha^{-1} (soil media) + 0.5 % $ZnSO_4$ solution (foliar spray) increased plant height of wheat crop to 41.8 %. The foliar spray of 0.05 %Zn resulted in 69–78 % in wheat crop (Sultana et al., 2018). Moreover, Chaab et al. (2011) reported that LAI was enhanced with Zn application to wheat crop. It is evident accumulation of Zn in meristematic tissues leads to better LAI (Pearson and Rengel, 1995, Gowthami and Ananda, 2018).

Heat unit efficiency (HUE) determines the conversation of heat energy into dry matter and yield per unit degree days is determined by heat unit efficiency (HUE) per unit growing degree days. It is affected by

Table 3
Partial budget analysis of wheat cultivars fertigated with Zn fertilizer.

Treatment		Total costs that vary (PKR ha^{-1})	Wheat grain yield (t/ha)	Grain yield increase over control (t/ha)	% yield increase over control	Value of increased yield (PKR ha^{-1})	Value cost ratio (VCR)
kg $ZnSO_4$ ha^{-1}	Cultivars						
T1	Zincol-2016	––	2.7			––	––
	Akbar-2019	––	2.8			––	––
	FSD-2008	––	2.5			––	––
	Anaj-2017	––	2.5			––	––
T2	Zincol-2016	5100	2.9	0.2	7.40	11,600	2.27:1
	Akbar-2019	5100	3.1	0.3	10.7	17,400	3.41:1
	FSD-2008	5100	2.7	0.2	8.0	11,600	2.27:1
	Anaj-2017	5100	2.7	0.2	8.0	11,600	2.27:1
T3	Zincol-2016	4400	2.9	0.2	7.4	11,600	2.63:1
	Akbar-2019	4400	3.1	0.3	10.7	174,000	3.95:1
	FSD-2008	4400	2.7	0.2	8.0	11,600	2.63:1
	Anaj-2017	4400	2.7	0.2	8.0	11,600	2.63:1
T4	Zincol-2016	7300	3.1	0.5	18.5	29,000	3.97:1
	Akbar-2019	7300	3.3	0.6	21.4	34,800	4.76:1
	FSD-2008	7300	2.9	0.5	20.0	29,000	3.99:1
	Anaj-2017	7300	2.9	0.5	20.0	29,000	3.99:1

Calculation based on: marketing of grain produce = PKR 58,000 ton^{-1}; cost of Zn $SO_4\cdot7H_2O$ (33 %) = PKR 300 kg^{-1}; variable labor charges for soil application and foliar sprays. T1 = control; T2 = (Soil application) = 15 kg $ZnSO_4\cdot7H_2O$ ha^{-1}; T3 (Foliar application) = $ZnSO_4\cdot7H_2O$ solution 1 % (0.5 %+0.5 %) at tillering and anthesis stages; T4 (Soil + Foliar application) = 15 kg $ZnSO_4\cdot7H_2O$ ha^{-1} (soil applied) and Foliar spray of $ZnSO_4\cdot7H_2O$ solution 1 % (0.5 %+0.5 %) at tillering and anthesis stages.

Table 4
Economic analysis of wheat cultivars fertigated with Zn fertilizer.

Treatment	Total input cost that varies (PKR ha^{-1})	Wheat grain yield (t/ha)	Grain yield increase over control (t/ha)	Gross value of total grain yield (PKR ha^{-1})	Marginal benefit over costs and control (PKR ha^{-1})	Marginal rate of return over investment in $ZnSO_4$ (%)
T1	–	3.05	–	176,900	–	–
T2	5100	3.40	0.35	197,200	20,300	398.04
T3	4400	3.50	0.45	203,000	26,100	593.18
T4	7300	4.00	0.95	232,000	55,100	754.48

Calculation based on: marketing of grain produce = PKR 58,000 ton^{-1}; cost of Zn $SO_4\cdot7H_2O$ (33 %) = PKR 300 kg^{-1}; variable labor charges for soil application and foliar sprays. T1 = control; T2 = (Soil application) = 15 kg $ZnSO_4\cdot7H_2O$ ha^{-1}; T3 (Foliar application) = $ZnSO_4\cdot7H_2O$ solution 1 % (0.5 %+0.5 %) at tillering and anthesis stages; T4 (Soil + Foliar application) = 15 kg $ZnSO_4\cdot7H_2O$ ha^{-1} (soil applied) and Foliar spray of $ZnSO_4\cdot7H_2O$ solution 1 % (0.5 %+0.5 %) at tillering and anthesis stages.

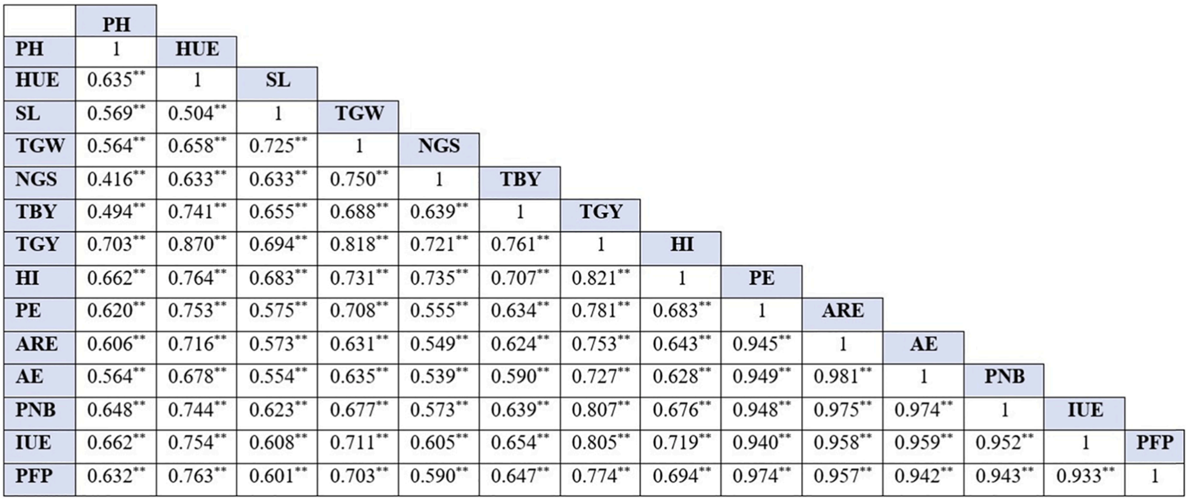
Table 5
Economic analysis [net present worth (NPW)] of wheat cultivars fertigated with Zn fertilizer.

Treatment	Cost of fertilizer applied (PKR ha^{-1})	Wheat grain yield (t/ha)	The open market value of grain produced (PKR ton^{-1})	Total cost (PKR ha^{-1})	Total Revenue (PKR ha^{-1})	Net present worth (PKR ha^{-1})
T1	–	3.05	58,000	115,000	176,900	61,900
T2	5100	3.40	58,000	120,100	197,200	77,100
T3	4400	3.50	58,000	119,400	203,000	83,600
T4	7300	4.00	58,000	122,300	232,000	109,700

Calculation based on: marketing of grain produce = PKR 58,000 ton^{-1}; cost of Zn $SO_4\cdot7H_2O$ (33 %) = PKR 300 kg^{-1}; variable labor charges for soil application and foliar sprays. T1 = control; T2 = (Soil application) = 15 kg $ZnSO_4\cdot7H_2O$ ha^{-1}; T3 (Foliar application) = $ZnSO_4\cdot7H_2O$ solution 1 % (0.5 %+0.5 %) at tillering and anthesis stages; T4 (Soil + Foliar application) = 15 kg $ZnSO_4\cdot7H_2O$ ha^{-1} (soil applied) and Foliar spray of $ZnSO_4\cdot7H_2O$ solution 1 % (0.5 %+0.5 %) at tillering and anthesis stages.

environmental factors, plant species and their genetic makeup, plantation time and density in relation to different agro-ecological zones (Sattar et al., 2015). The outcomes of our data revealed that wheat cultivars especially Akbar-2019 and Zincol-2016 better utilized light energy after fertigation with Zn. Sattar et al. (2015) stated that crops with better HUE utilizes solar energy more efficiently accelerating growth process. The availability of favorable temperatures results in uplift of different physio-chemical processes that ultimately results in better yield production per unit area. There are estimations that with one degree (°C) increase in temperature results in 6 % decrease in yield (Asseng et al., 2015).

The cereals are the main source dietary fibers, carbohydrates, proteins and lipids. A considerable increase in protein and fat contents was observed at T4 in all wheat cultivars. Kutman et al. (2012) stated that variation in protein content in wheat grain could be due to variation in grain size. The α-amylase is present in plants during germination stage



	PH	HUE	SL	TGW	NGS	TBY	TGY	HI	PE	ARE	AE	PNB	IUE	PFP
PH	1													
HUE	0.635**	1												
SL	0.569**	0.504**	1											
TGW	0.564**	0.658**	0.725**	1										
NGS	0.416**	0.633**	0.633**	0.750**	1									
TBY	0.494**	0.741**	0.655**	0.688**	0.639**	1								
TGY	0.703**	0.870**	0.694**	0.818**	0.721**	0.761**	1							
HI	0.662**	0.764**	0.683**	0.731**	0.735**	0.707**	0.821**	1						
PE	0.620**	0.753**	0.575**	0.708**	0.555**	0.634**	0.781**	0.683**	1					
ARE	0.606**	0.716**	0.573**	0.631**	0.549**	0.624**	0.753**	0.643**	0.945**	1				
AE	0.564**	0.678**	0.554**	0.635**	0.539**	0.590**	0.727**	0.628**	0.949**	0.981**	1			
PNB	0.648**	0.744**	0.623**	0.677**	0.573**	0.639**	0.807**	0.676**	0.948**	0.975**	0.974**	1		
IUE	0.662**	0.754**	0.608**	0.711**	0.605**	0.654**	0.805**	0.719**	0.940**	0.958**	0.959**	0.952**	1	
PFP	0.632**	0.763**	0.601**	0.703**	0.590**	0.647**	0.774**	0.694**	0.974**	0.957**	0.942**	0.943**	0.933**	1

Fig. 5. Pearson correlation analysis of different parameters of four wheat cultivars reveals the effect of Zn fertilization. PH: plant height; HUE: heat unit efficiency: SL: spike length; TGW: 1000 grain weight; NGS: number of grains per spike; TBY: total biological yield; HI: harvest index; PE: physiological efficiency; ARE: apparent recovery efficiency; AE: agronomic efficiency; PNB: partial nutrient budget; IUE: internal use efficiency; PFP: partial factor productivity.

and pre-maturity stage of grain development where it is deposited in endosperm after maturity (Marchylo et al., 1980, Sudha and Stalin, 2015). There are confirmations that higher amount of α-amylase in wheat prompted decrease in grain yield, quality also economic loss. The maintenance of α-amylase at lower levels brings about further improves bread quality regarding textural properties and decreasing flexibility and lessening harm to dough (Barrera et al., 2016).

The quantity of Zn to be utilized as fertilizer for wheat crop has a significant importance as Zn fertilization results in enhancement of Zn contents that uplift the uptake of other minerals (N, P, K, Fe). Sultana et al. (2018) also reported that foliar feeding of durum wheat (G-3 genotype) with $ZnSO_4$ significantly enhanced Zn contents in grain. Results of this experiment also revealed that Zn contents in wheat grains were uplifted after Zn fertilization in all cultivars especially in Akbar-2019.

Zinc nutrient had a greater role in improving yield and yield components of wheat crop. The value of application of Zn fertilizer to wheat had a significant importance, particularly for growing of crops in alkaline- calcareous soils leading to better yield (Tawfik, 2022). Biological yield is an element of grain and straw yield addressing vegetative and reproductive development. The higher biological yield was obtained by the wheat crop at T4. The higher availability of Zn in relation to different supplements brought about better vegetative development with the beginning of improvement at the seedlings stage, consequently, higher creation of biomass yield. Previously Cakmak (2012) stated that Zn fertilizer increased biological yield in wheat. The cultivars on the other hand exhibited higher number of tillers, spike length, thousand grain weight and grain yield with Zn application especially at T4. Besides, the presence of higher Zn in the soil and it's uptake by the plants results in enhanced grain yield with higher proportions of protein and starch contents in the grains (Cakmak, 2012).

As Zn is highly mobile element in germinating seedlings and vegetative tissues its exogenous application results in increased grain Zn content (Palmgren et al., 2008). Boosted levels of Zn in plant tissues on the other hand enhanced the uptake of N, P, K and Zn while reduced Fe contents in wheat grains (Sher et al., 2022). The Zn bearing an essential component helps in up-regulation the efficiency of phosphate transporters, however, its deficiency may cause increased in P-uptake up to the toxic level. Aslam et al. (2014) described that Zn fertigation through external means enhanced the uptake of K^+ due to opening of K^+ channels by increased concentration of Zn in plant. Similarly, the increase in Zn content in grains after foliar Zn spray, enhanced Zn mobility in phloem and its rapidly translocation to the developing grains (Ghasal et al., 2017, Ahmed et al., 2019). However, Fe contents in grains were lowered after Zn fertilization in all wheat cultivars. Jat et al. (2018) reported similar results that Fe contents were reduced to 9 % and 11 % after application of 3.0 and 6.0 kg ha^{-1} Zn respectively.

The fundamental criteria for proper development wheat crops lies in the fact that nutrients are used efficiently. After Zn fertigation the nutrient use efficiency of wheat cultivars was enhanced significantly especially at T4. The partial factor productivity (PFP) evaluated the worth of added Zn manure to wheat crops. The findings of this study indicated that efficiency of PFP was enhanced with Zn fertilization (T2-T4) and also showed positive correlation with yield attributes. The internal use efficiency (IUE) was greatly stimulated after in response to Zn fertilization. Kumar et al. (2022) also reported that Zn nutrient use efficiency could be improved by application of Zn fertilizer either in the soil and / or foliar feeding in wheat crop.

The agronomic efficiency (AE) determines the efficiency of Zn fertilizer towards increasing genetic yield potential of crop. While apparent recovery efficiency (ARE) and physiological efficiency (PE) determines the amount of Zn accumulated in the above ground parts and its effectiveness over crop seasons (Dai et al., 2010). The application of Zn either foliar or soil media enhanced AE, PE and ARE more significantly at T4. Previously Kumar et al. (2022) reported that AE was increased by addition of Zn fertilizer to a wheat crop.

The ultimate aim of the farmer is to get higher yield return after selecting best seed and usage of proper chemical fertilizers. Thus, it is basic to assess the income of investment on a crop. In this case, economic analysis was done to decide the benefit of adding Zn fertilizer to wheat crops which was improved to significant level with Zn fertilization (T2-T4). The importance of adding minerals was to increase the efficiency of field per unit area and to raise income to maintain the farming business a profitable one (Program, 1988). The marginal rate of return (MRR) and the profit of the former is associated to demand and market price. The attainment of 100 % MRR would be more profitable and economical for farmers (Program, 1988). Similarly, value cost ratio (VCR) ranges from 3:1 to 2:1 for wheat in irrigated area. The highest VCR value of 4.76:1 was observed in Akbar-2019 after application of Zn fertilizer (T4). It has been reported that a VCR of 3.0:1 – 7.0:1 is considered profitable (Zou et al., 2012).

5. Conclusion

The Zn fertilization on wheat cultivars exhibited positive effect on vegetative growth with respect to plant height, leaf area index, and heat-unit efficiency. Similarly, protein, fat, ash and phytic acid contents were increased while α-amylase contents were decreased in grains after Zn fertigation in any mode. The Zn fertilization resulted in appreciable increased in the determinants of grain yield and harvest index and ultimately better biological yield. The grain yield increased from 3.0 to 4.3 t/ha in various treatments. The highest values of these parameters were recorded at T4. The Zn nutrient fertilizer use efficiency was also improved after Zn application. Maximum values of minimum MRR, VCR and NPW were achieved to the amount of 755 %, 4.76:1 and PKR 109,700 compared to 398 %, 2.28:1 and PKR 61,900, respectively at T4. Concludingly, the cultivars Zincol-2016 and Akbar-2019 were more economical and profitable for general cultivation as compared to Anaj-2017 and FSD-0008 in sandy loam soils. In the arena of "Climate Smart Agriculture", the mineral nutrition is the tryst for potential increase in crop productivity and resilient to climate change. Furthermore, the fertilizer industry will be benefitted greatly by coating (<0.15 mm) urea, NP and NPK compound fertilizer with 1 % $ZnSO_4 \cdot 7H_2O$ nutrient.

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Consent to participate.

All authors consent to participate in the manuscript publication

Consent for publication

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Muhammad Iqbal Makhdum: Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Muhammad Abid:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Sibgha Noreen:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Rafa Almeer:** Writing – review & editing, Validation, Conceptualization. **Vaseem Raja:** Writing – review & editing, Validation, Resources, Conceptualization. **Muhammad Salim Akhter:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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