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Soil and Foliar Zinc Regulate Phenology, Canopy Development and Biomass Partitioning of Bread Wheat under Semi-Arid Conditions

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ABSTRACT

In many alkaline and calcareous soils zinc deficiency is a limiting factor for crop growth, but the relative importance of soil rate, foliar concentration and spray timing to wheat growth dynamics cannot be differentiated. The field experiment was carried out at Agronomy Research Farm, The University of Agriculture, Peshawar, Pakistan in winter season 2021-2022. The experimental design was 3 x 3 x 2 factorial randomized complete block with three replications and included a booting x anthesis timing of foliar Zn application in addition to soil Zn levels (5, 10 and 15 kg ha-1) and foliar Zn (0.2, 0.4 and 0.6%), and an untreated control. The application rate of soil Zn was zinc sulphate at sowing. Increasing soil Zn from 5 to 15 kg ha-1 reduced days to booting from 87.3 to 82.6, days to anthesis from 131.0 to 125.6 and days to maturity from 165.5 to 160.8. The same increase raised plant height from 90.5 to 107.1 cm, leaf area from 101.4 to 110.4 cm2 tiller-1, spike density from 262.2 to 308.2 m-2, total dry weight at anthesis from 416.5 to 484.4 g m-2 and total dry weight at maturity from 443.9 to 512.1 g m-2. At 0.6%, foliar Zn produced greater biomass production and canopy traits compared to lower concentrations and foliar application at anthesis. The interactions among the factors were non-significant for all of the growth traits measured, which means that their effects were largely additive. The overall

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conclusion is that soil Zn at 15 kg ha-1 coupled with foliar treatment at booting stage is an effective growth management technique for WADAN–17 wheat under the conditions tested.

Keywords: Biomass Partitioning; Foliar Nutrition; Phenology; Semi-Arid Agriculture; Triticum Aestivum; Zinc Sulphate

Introduction

In South Asia, wheat to meet food security requirements is the focus and productivity relies on the ability of crops to take up nutrients from soils that are often alkaline, calcareous and organic matter deficient. Limitation of micronutrients can be masked under macronutrient fertilization, as crop stands can be successfully established and leaf expansion, enzyme activity, reproductive development and dry-matter accumulation may be limited. Zinc is particularly vital in such environment due to its roles in enzyme activation, protein synthesis, auxin metabolism, membrane integrity and reproductive development (Cakmak, 2008; Alloway, 2009).

The agronomic response to Zn varies depending on placement, rate and crop stage. Root zone availability can be maintained by soil application during vegetative growth; however, Zn can be bound or precipitated in high pH soils. Part of this soil limitation can be overcome by foliar application of Zn and can provide Zn when the leaf surface is in high demand, but absorption and redistribution can depend on leaf age at time of application, spray concentration and time between spray and grain filling. Root uptake and shoot translocation and remobilization are thus coupled, and not interchangeable delivery mechanisms (Liu et al., 2019; Cakmak et al., 2010).

Recent field and controlled-environment studies have validated increased plant height, water relations, biomass and yield-related properties with Zn fertilization; however, genotypic and environmental variation in response to fertilization exists. Application of nutrient programmes based on balanced zinc has improved the biomass of cereals (Amanullah et al., 2019) while foliar nutrient application has improved the performance of wheat in field conditions (Arif et al., 2006). Previous studies showed that foliar Zn gave better morpho-physiological performance under water limitation (Sattar et al., 2022) and factorial field testing under the current study revealed significant differences among wheat genotypes for 0.4 and 0.6% zinc sulphate application. The use of integrated soil and foliar application has also boosted productivity and grain available zinc in both biofortified and non-biofortified varieties (Nayak et al., 2023). The results confirm that the routes and concentrations should be evaluated simultaneously, instead of individually considering a single Zn treatment.

Regional research supports a broader site-specific approach to crop growth and biomass management. Biochar combined with phosphorus or beneficial bacteria has improved maize nutrient use, growth, and biomass under productive and contaminated-soil conditions (Farooq et al., 2026; Jalal et al., 2026; A. Khan et al., 2026). Although focused on horticultural crops, local field studies show that canopy protection and final productivity also depend on varietal resistance and timely pest management (Anees et al., 2026; Rehman et al., 2026). Water-quality assessments in Peshawar and Mohmand further highlight the need to align nutrient and irrigation management with locally measured resource conditions (Khan et al., 2025; Khan &

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Khan, 2026).

The present study isolated the main effects of soil Zn rate and of foliar Zn concentration and timing of spraying of wheat phenology, canopy development and dry-matter partitioning effects. There were three goals: First, to measure differences in crop developmental time; second, to test for any effects of Zn management on plant height, leaf area, and spike density; and third, to assess biomass changes in leaves, stems, and spikes at anthesis and physiological maturity. We hypothesized that increasing soil and foliar Zn supply would speed development and increase biomass, with the former being more effective than the latter, since we would expect the former to have a greater effect on the plant than the latter.

Materials and Methods

Experimental site and design

The field experiment was carried out in the Agronomy Research Farm of The University of Agriculture, Peshawar, Pakistan in winter growing season 2021-2022. The site is a semi-arid irrigated production site. Wheat cultivar Wadan-17 was sown on 5th November, 2021 at a seed rate of 120 kg ha-1 and harvested during May 2022. The size of individual plots was 2.4 x 2.4 m, and rows were spaced at 0.30 m.

The treatments were laid out on a randomized complete block design with three replications. The factorial part involved three soil Zn rates (5, 10 and 15 kg ha-1), three foliar Zn concentrations (0.2, 0.4 and 0.6%) and two foliar application times (booting and anthesis) which resulted in 18 combinations. There was a no-Zn control in all replications and 19 treatments and 57 experimental units. The source of Zn was zinc sulphate. Rate of soil Zn application was at sowing and foliar solutions were sprayed at the target crop stage. Other management practices were maintained constant and five irrigations were made after establishment and at tillering, heading, anthesis and grain filling.

Table 1 Treatment structure used in the field experiment.

Component	Levels	Application point
Soil Zn	5, 10, 15 kg ha-1	At sowing
Foliar Zn	0.2, 0.4, 0.6%	Assigned crop stage
Foliar timing	Booting, anthesis	Single stage-specific spray
Control	No soil or foliar Zn	Not applicable

The factorial treatment set contained 18 combinations; the untreated control was analyzed through a planned control-versus-rest contrast.

Measurements

The number of days to booting were calculated from sowing to when 50% of plants in a plot had reached the booting stage. Days to anthesis were recorded when over 80% of plants reached anthesis, whilst days to maturity were counted from sowing to physiological maturity. The height of the plants was recorded approximately before

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harvesting on 10 representative plants per plot. The leaves were counted on 10 representative tillers. Leaf area per tiller was calculated from length and maximum width of the leaves by multiplying by a correction factor of 0.75.

The spike density has been calculated according to the number of spikes counted in the measured row lengths and converted to spikes m-2. At anthesis and physiological maturity, biomass sampling was carried out by taking a 1-m row from each experimental unit. Samples were sun dried to constant mass, then the leaves, stems and spikes were separated, weighed and converted to g m-2 on the basis of the area of ground sampled. The three components were added to give total dry weight.

Statistical analysis

The analysis of data was done based on randomized complete block design. The factorial treatment sum of squares was broken down into the effect of soil Zn, foliar Zn, foliar timing and their interaction. A planned contrast was used to compare the untreated control to the mean of the factorial treatments. The least significant difference test (LSD) at P <= 0.05 was used to separate means according to Steel et al. (1996). All means reported in this manuscript were confirmed by replicated values at the plot level in the appendices of the thesis.

Results

Crop phenology

Crop development was significantly affected by soil Zn. Days to booting declined progressively from 87.3 at 5 kg Zn ha-1 to 85.0 at 10 kg ha-1 and 82.6 at 15 kg ha-1. The pattern was the same for days to anthesis, which dropped from 131.0 to 128.2 and 125.6 days. The factorial ANOVA of foliar concentration and spray timing did not significantly affect the booting and anthesis, although there were slight differences in the means. In the control, it took 89.3 days to boot and 131.0 days to reach anthesis, whereas the same for the Zn treated plots were 85.0 and 128.3 days, respectively.

All three Zn factors had an effect on physiological maturity. The crop duration was decreased by 4.7 days with the application of soil Zn levels ranging from 5 to 15 kg ha-1. Foliar Zn at 0.6% and 0.2 % matured 1.7 days and 1.0 day respectively earlier than spraying at anthesis, which is the same as spraying at booting. The untreated control took 169.0 days to mature while the treatment mean was 163.1 days. No interactions either two-way and three-way were statistically significant for the phenological variables.

Table 2 Main-effect means for wheat phenology.

Factor	Level	Booting (days)	Anthesis (days)	Maturity (days)
Soil Zn (kg ha-1)	5	87.3	131.0	165.5
	10	85.0	128.2	162.9
	15	82.6	125.6	160.8

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Factor	Level	Booting (days)	Anthesis (days)	Maturity (days)
Foliar Zn (%)	0.2	85.2	128.3	163.9
	0.4	85.1	128.3	163.0
	0.6	84.7	128.2	162.3
Timing	Booting	85.0	128.0	162.6
	Anthesis	85.0	128.6	163.6

Factorial means exclude the untreated control. Soil Zn significantly affected all three traits; foliar Zn and timing significantly affected maturity only. All interactions were non-significant.

Canopy development and stand structure

Plant height increased from 90.5 cm at 5 kg soil Zn ha-1 to 107.1 cm at 15 kg ha-1. Increases in foliar Zn from 0 to 0.2%, 0.4 to 0.6%, resulted in mean plant height of 96.4 to 101.3 cm respectively. Booting stage application resulted in a 3.2 cm increase in plant height over anthesis stage application. The average height of treated crop was 21.8 cm more than the control crop. Soil Zn, foliar Zn and the contrast between control and rest were significant, whereas all interactions were non-significant.

The coordinated response was observed between the leaf area and spike density. Leaf area increased by 8.8% between 5 and 15 kg soil Zn ha-1 and by 9.9% between 0.2 and 0.6% foliar Zn. Leaf area was 9.0% higher in booting-stage application compared to the anthesis-stage application. The spike density increased from 262.2 to 308.2 m-2 within the soil Zn gradient and from 277.6 to 293.0 m-2 within the foliar Zn concentration gradient. Leaf area per tiller did not change significantly as a result of better canopy development, thus the increased canopy development was principally due to increased leaf expansion and stand reproductive density and not an increase in leaf number per stand.

Table 3 Main-effect means for canopy and stand traits.

Factor	Level	Height (cm)	Leaves tiller-1	Leaf area (cm2)	Spikes m-2
Soil Zn (kg ha-1)	5	90.5	4.67	101.5	262.2
	10	98.3	4.78	107.3	284.8
	15	107.1	4.39	110.4	308.2
Foliar Zn (%)	0.2	96.4	4.72	101.2	277.6
	0.4	98.2	4.44	106.8	284.6
	0.6	101.3	4.67	111.2	293.0

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http://amresearchreview.com/index.php/Journal/about

Factor	Level	Height (cm)	Leaves tiller-1	Leaf area (cm2)	Spikes m-2
Timing	Booting	100.3	4.59	111.0	287.2
	Anthesis	97.0	4.63	101.8	282.9

Leaves per tiller was not significantly affected by any Zn factor. Main effects were significant for plant height, leaf area and spikes m-2; interactions were non-significant.

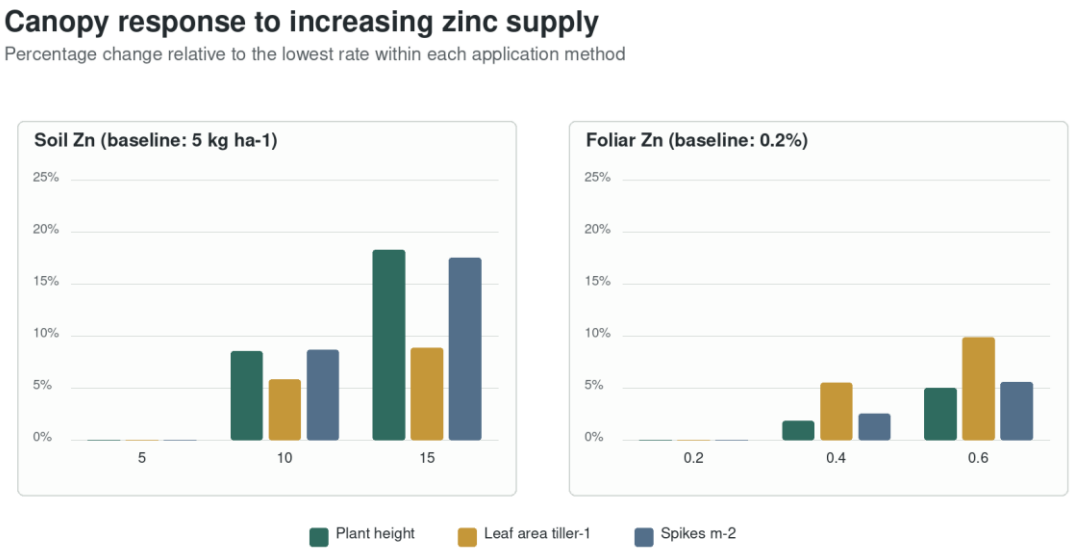

Figure 1 Relative response of plant height, leaf area per tiller and spike density to increasing soil and foliar Zn rates.

Biomass accumulation and partitioning

In both sampling times, zinc management resulted in higher mass of all plant components. At anthesis, total dry weight increased from 416.5 g m-2 at 5 kg soil Zn ha-1 to 484.4 g m-2 at 15 kg ha-1. The corresponding foliar means increased from 421.2 g m-2 at 0.2% to 481.5 g m-2 at 0.6%. The 466.4 g m-2 of the foliar treatment was obtained against 435.7 g m-2 for the application done at anthesis. The untreated control produced 46.9, 72.7 and 176.4 g m-2 of leaf, stem and spike dry weight at anthesis, respectively, while the treated plots produced 86.1, 137.1 and 227.9 g m-2 of leaf, stem and spike dry weight, respectively, at anthesis.

The treatment effects remained up to adulthood. The total dry biomass grew from 443.9 to 512.1 g m-2 at the lowest and highest soil Zn rates while increasing from 448.6 to 510.2 g m-2 at the 0.2 and 0.6% foliar Zn rates. Application at booting stage resulted in 503.0 g m-2 at maturity, which was 10.5% more than application at anthesis. The mean for the control (no-Zn) was 320.6 g m-2 and for the treated group it was 479.1 g m-2. Component response was internally consistent, at the maximum soil rate, leaf, stem and spike dry weight were 116.9, 151.5 and 243.7 g m-2 respectively.

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Volume 4, Issue 6 (2026)

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http://amresearchreview.com/index.php/Journal/about

The effects of all soil, foliar and timing treatments on biomass components were significant, as was the control-versus-rest contrast. All soil x foliar, soil x timing or foliar x timing x three-way interactions were not significant. The lack of interaction means that there was little deviation from additivity within the range of Zn components tested.

Table 4 Dry-matter partitioning at physiological maturity (g m-2).

Factor	Level	Leaves	Stems	Spikes	Total
Soil Zn (kg ha-1)	5	97.6	126.0	220.2	443.9
	10	108.8	139.8	232.8	481.5
	15	116.9	151.5	243.7	512.1
Foliar Zn (%)	0.2	98.0	128.2	222.4	448.6
	0.4	107.6	139.3	231.7	478.6
	0.6	117.8	149.7	242.7	510.2
Timing	Booting	112.1	144.6	246.3	503.0
	Anthesis	103.5	133.6	218.2	455.3

All three main effects and the control-versus-rest contrast were significant (P <= 0.05) for each biomass component. All factorial interactions were non-significant.

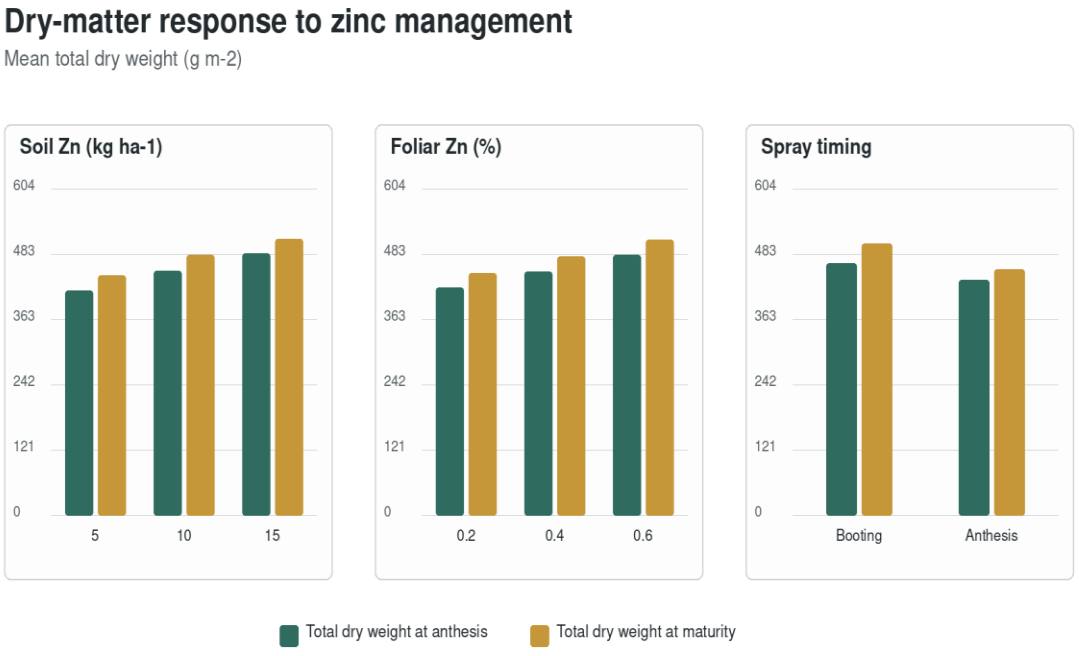

Figure 2 Total dry weight at anthesis and physiological maturity as affected by soil Zn rate, foliar Zn concentration and foliar application timing.

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http://amresearchreview.com/index.php/Journal/about

Discussion

The uniform results over the different phenologies, canopy characteristics and dry-matter production suggest that Zn supply was a substantial growth constraint in the experimental environment. The enzymes requiring Zn are involved in carbon metabolism and protein synthesis, and also Zn plays a role in regulating auxin and membrane function (Cakmak, 2008; Alloway, 2009). These processes could offer a reasonable explanation for observed increase in plant height and leaf area and plant biomass with increasing soil Zn. The background Zn availability was limited to maintain the same growth rate as fertilized plots as indicated by the strong response of the untreated control.

The advancing of the booting stage, anthesis and maturity with increasing soil Zn is of agronomical significance in the semi-arid environment. If development occurs earlier, exposure to terminal heat can be minimized if there is enough canopy development and assimilate accumulation. This experiment did not cause premature growth cessation since biomass and spike density grew together. Similar reduction in phenological duration and response to Zn nutrient management were reported in wheat-based systems; soil Zn was shown to have an impact on the uptake and translocation of the nutrient after anthesis through its effects on root activity and Zn availability (Liu et al., 2019).

The foliar response depended more on concentration and timing than did early phenology. Increased in plant height, leaf area per plant, spike density and plant biomass with foliar Zn at 0.6% that is consistent with the reports of Modification of wheat plant growth and yield related traits with the foliar application of 0.4-0.6% zinc sulphate (Azeem et al., 2023). Tissue demand can be met very quickly if the root zone Zn is limited and physiological studies indicate that foliar Zn application leads to improvement in the relative water status, gas exchange and antioxidant protection (Sattar et al., 2022). These are interpretations rather than direct observations in the current study since the tissue Zn and photosynthesis were not measured.

The best spray time for canopy expansion and biomass was booting. This stage is before rapid spike growth and high assimilate demand; absorbed Zn will allow the leaf function and development of reproductive sink to occur for a longer period than an anthesis spray. The previous studies also determined that foliar application of Zn could be beneficial in wheat at specific growth stages, namely at growth stage 25 (El-Dahshouri et al., 2017) and growth stage 57 (Esfandiari et al., 2016). Foliar Zn can also be applied primarily for grain enrichment, and late applications can be beneficial even if vegetative biomass is less responsive (Amaral & Brown, 2022; Cakmak et al., 2010). The best stage will then be determined by the production objective, such as enhancing crop growth or grain yield and grain Zn concentration.

The non-significant interactions warrant practical consideration. In the range tested, the higher soil Zn level caused an increase, and the higher the foliar concentration, the earlier the date of application in the booting stage, and the direction of the increase was independent of one another, that is, the higher the level of the one factor, the higher the level of the other factor, and the earlier the other factor was applied, the earlier the first factor was applied. This allows for a simple, joint recommendation, but not a conclusion of economic necessity for any individual component. Before

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suggesting the whole package in the farm, a treatment-cost analysis and a response curve based on soil-test would be necessary. Soil and foliar strategies have been effective in other locations in enhancing productivity and nutrition quality of crops (Nayak et al., 2023), but the most effective soil/foliar strategy may depend on soil pH, extractable Zn, cultivar and seasonal conditions (Yaseen & Hussain, 2021).

The study has three main limitations. It was implemented at a single site, in one season; Zn concentrations of plants and grains were not measured; and no soil physicochemical data were provided in source thesis. Thus, the outcomes reflect agronomic response under the conditions tested, but not necessarily measure Zn-use efficiency, or biofortification. Multi-location validation should combine yield and biomass data, soil-test Zn, leaf Zn, and grain Zn data with weather and partial-budget data.

Conclusions

Soil Zn rate was the major factor affecting development timing whereas soil rate, foliar concentration and spray timing affected canopy development and biomass. The 15 kg Zn ha-1 application resulted in the smallest crop duration and maximum plant height, leaf area, spike density and dry matter. No antagonistic interactions were observed between factors and foliar Zn at 0.6% plus application at booting further improved growth. The application of 15 kg soil Zn ha-1 combined with 0.6% foliar Zn at booting stage is recommended as the most effective treatment for wheat Wadan-17 under the condition of Peshawar. Regional recommendation should follow, after seasonal and soil Zn class validation.

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