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ARTICLE

Yield and Physiological Responses of Two Cultivars of Oat (*Avena sativa* L.) to Varying Levels of Foliar Micronutrient Fertilization

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ABSTRACT

The low availability of micronutrients in alkaline soils is a major constraint limiting oat (*Avena sativa* L.) productivity. This study evaluated the effects of foliar application of chelated micronutrients on the yield and physiological performance of two oat cultivars grown under alkaline soil conditions. A field experiment was conducted during the 2024–2025 winter growing season in Al-Khidhir District, Al-Muthanna Governorate, Iraq. The experiment was arranged in a randomized complete block design (RCBD) with a split-plot arrangement and three replications. Two oat cultivars (Al-Juda and Shifa) were assigned to the main plots, while four foliar treatments consisting of distilled water (M0) and three levels of chelated micronutrients containing iron, zinc, and manganese (M1, M2, and M3) were allocated to the subplots. The results showed significant effects of cultivar, micronutrient level, and their interaction on most measured traits. The M2 treatment produced the highest values for yield components and physiological traits. Under this treatment, the Shifa cultivar achieved the highest number of panicles (410.7 m^{-2}), grains per panicle (71.8), 1000-grain weight (41.3 g), grain yield (5.60 t ha^{-1}), biological yield (13.95 t ha^{-1}), and harvest index (40.14%). These values were significantly higher than those obtained from the Al-Juda cultivar and the control treatment (M0). The superior performance of Shifa suggests a greater capacity to utilize foliar-applied micronutrients efficiently, resulting in improved assimilate partitioning and enhanced productivity. The findings indicate that integrating the Shifa cultivar with the M2 foliar micronutrient treatment provides an effective strategy for improving oat productivity under alkaline soil conditions and may contribute to more sustainable oat production in similar environments.

Keywords: *Foliar Fertilization; Genotype-by-environment Interaction; Chelated Elements; Physiological Efficiency.*

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INTRODUCTION

The oat crop (*Avena sativa* L.) is one of the most important winter cereal crops in the world. It has gained increasing importance because of its high nutritional value for both human and animal consumption. The oat grain is rich in soluble fibers such as beta-glucans, high-quality proteins, and unique antioxidants avenanthramides which provide different functional and health benefits (Montilla-Bascón *et al.,* 2024; Zhou *et al.,* 2025). Oats have critical growth periods comparable to those of other cereal crops, such as wheat and barley (Sadras and Lawson, 2013; Sadras *et al*., 2023).

Oat production is limited by large environmental and nutritional constraints, including the most serious micronutrient deficiency in soils, even more in calcareous or alkaline soils that are found in many agricultural environments. Oats require trace amounts of essential micronutrients like iron (Fe), zinc (Zn), and manganese but, their deficiency leads to the disruption of vital biophysiological processes (Fageria *et al*., 2011; Marschner, 2012; Römheld, 2020). *Nutrient Management in*

Agricultural Systems: Principles of Plant Nutrition. Springer Oat crops are recognized as one of the most sensitive to manganese deficiency, which affects photosystem II (PSII) function and hence appears as gray speck disease (Römheld and Kirkby, 2024). Zinc and iron deficiencies also inhibit the biosynthesis of plant hormones such as auxins, block cell division, and accelerate leaf senescence. Hence, these deficiencies have a negative impact on yield parameters and their components, including panicle number and grain weight (Broadley *et al*., 2012; Cakmak and Kutman, 2025).

Since most alkaline reaction soils fix micronutrients (Tripathi *et al*., 2015) applied to them through the soil, foliar application has been considered a very effective physiological alternative. This approach will ensure the direct uptake of elements by stomata and cuticle without depending on complex chemical reactions in the soil, thus improving nutrient use efficiency (Zulfiqar *et al.,* 2024). Recent studies indicate that crop genotype strongly influences the response to micronutrient fertilization. There is significant variation among oat cultivars in their physiological abilities to absorb, translocate, and remobilize micronutrients from vegetative parts as well as the capacity to allocate the developing grains during the grain-filling period (source and sink) (Lopez-Bellido *et al*., 2014; Fageria and Nascente, 2024; El-Sanusny *et al.,* 2025; Cakmak, 2008). This is an interaction that should be understood as a cornerstone in the identification of high-efficiency cultivars that can interact with environments to sustainably realize high productivity with varying levels of fertilizer to achieve a high harvest index.

This study was built on the above-mentioned assumptions and designed to test the hypothesis that raising the levels of foliar nutrition with chelated micronutrients (Fe, Zn, and Mn) could improve the physiological efficiency and yield components of two oat cultivars differently, based on their genetic variation. Accordingly, this experiment aims to determine the optimal fertilization level, evaluate the productive performance of the two cultivars, and select the most efficient combination to achieve the highest grain yield and harvest index in the study area.

MATERIALS AND METHODS

A field experiment was conducted in Al-Muthanna Governorate/Al-Warkaa District during the (2024–2025) agricultural season to investigate the effects of different levels of micronutrients on the grain yield of two oat cultivars. The experiment was carried out in a soil whose key chemical and physical characteristics are outlined in the Table 1.

Table (1) some chemical and physical characteristics of the field soil

Properties		Unit	Value
Physical	**Sand**	gm/kg^{-1} soil	270.00
	Silt		600.00
	Clay		130.00
	Soil texture	Loamy	
Chemical	**Ece**	dS m^{-1}	5.15
	Ph		7.17
	Organic mater	gm kg^{-1} soil	2.20
	Available Nitrogen		19.70
	Available Phosphorus	mg kg^{-1} soil	24.70
	Available Potassium		128.50

1. Experimental Design and Treatments

The field experiment was conducted according to a Randomized Complete Block Design (R.C.B.D) arranged in a split-plot layout with three replications, resulting in a total of 24 experimental units. The main plots were allocated to four levels of a chelated micronutrient mixture EDTA designated as M0, M1, M2, and M3. The mixture comprised three essential micronutrients for oat: Iron Fe, Zn and Mn. The treatments were applied as a foliar spray at two critical growth stages:

elongation and booting. The micronutrient levels were distributed as follows:

- Level 1 (M0): Control treatment, foliar sprayed with distilled water only.
- Level 2 (M1): Medium concentration level, containing 0.0 g/L of Fe 0.25 g/L of Zn, and 0.25 g/L of Mn.
- Level 3 (M2): High concentration level, containing 1.0 g/L of Fe, 0.5 g/L of Zn, and 0. g/L of Mn.
- Level 4 (M3): Very high concentration level, containing 1.5 g/L of Fe 0.75 g/L of Zn and 0.75 g/L of Mn.

Meanwhile, the sub-plots were assigned to the two cultivated oat cultivars: Al-Juda (V1) and Shifa (V2).

2. Field Operations and Soil Preparation

The experimental field was prepared by performing two perpendicular plowings using a moldboard plow following the pre-planting irrigation process subsequently. The soil was pulverized using disc harrows and subsequently leveled with a mechanical land leveler to produce a uniform seedbed. Based on the designated experimental design, the field was divided into plots, with each experimental plot measuring 4 (2m x 2m). Planting was performed in rows spaced 20 cm apart. A 0.5 m buffer zone was maintained between adjacent sub-plots to minimize treatment interference and prevent cross-contamination.

Studied Traits

1. **Number of Fertile Panicles m^{-2}:** Calculated at physiological maturity by counting the total number of panicles harvested from two central rows within each experimental unit.
2. **Number of Grains per Panicle (grain $panicle^{-1}$):** Determined by averaging the grain count of ten randomly selected panicles per plot after manual threshing.
3. **1000-Grain Weight (g)** Evaluated by taking a random sample of 1000 grains from each experimental unit and weighing them was using a high-precision sensitive balance.
4. **Grain Yield ton/ha^{-1}:** Estimated from the plants harvested within the two central rows of each plot. Following manual threshing and separating the grains from the straw, the grain weight was recorded and converted to tons per hectare ton/ha^{-1}.
5. **Biological Yield ton/ha^{-1}:** Determined by weighing the entire biomass (straw + grains) harvested from the two central rows after complete oven-drying. The total dry weight was then converted from g m^{-2} to ton/ha^{-1}
6. **Harvest Index %:** Calculated based on the harvested sample according to the formula proposed by Donald (1962):
   Harvest Index (HI) = [Grain Yield/Biological Yield] × 100

3. Statistical Analysis

The collected data for growth and yield traits were statistically analyzed using the Genstat software package. Treatment means were compared using the Least Significant Difference LSD at a probability level of, in accordance with the procedures outlined by Al-Rawi and Khalaf Allah (1980).

RESULTS AND DISCUSSION

1. Number of Panicles per Square Meter (panicles/m²)

The results revealed significant variations in the number of panicles/m² between the two studied cultivars. Cultivar (V2) significantly outperformed Cultivar (V1), recording the highest mean of 352.5 panicles/m² compared to 323.75 panicles/m² for V1; this observed variance exceeded the Least Significant Difference Value (Table 2). This superiority is primarily attributable to genetic divergence between the two cultivars; V2 exhibits a higher capacity for generating

effective, productive tillers, alongside a distinct efficiency in mitigating early tiller mortality. This resilience stems from its superior competitive advantage for available resources namely light and water which ultimately enabled a larger proportion of tillers to progress to the panicle initiation stage and successfully develop panicles. Furthermore, foliar application of micronutrients induced a significant increase in the number of panicles/m². The F2 treatment level significantly surpassed the control (F0), yielding the highest mean of 372.5 panicles/m², whereas F0 recorded the lowest mean of 295.0 panicles/m², thereby exceeding the LSD threshold of 18.5.

This enhancement can be ascribed to the vital role of zinc in synthesizing active auxins, which stimulate cell division within apical meristems and activate basal buds to produce new tillers. Additionally, the availability of iron and manganese (Mn) during the early vegetative growth phases enhanced photosynthetic efficiency, thereby provisioning the metabolic energy and carbohydrates required to sustain tiller growth, ensure survival, and facilitate their transition into fully matured panicles (Marschner, 2012). The findings also demonstrated a significant two-way interaction, reflecting a highly synergistic response between the genetic architecture of V2 and the optimal concentrations of micronutrients. This interplay indicates that foliar fertilization successfully triggered the latent genetic potential of V2 regarding productive vegetative tillering, maximizing its physiological efficiency.

Table (2) Effect of micronutrient foliar fertilization levels on the number of tillers/m² for two oat cultivars

Foliar Fertilization Levels	First Cultivar	Second Cultivar	Fertilization Means
Control	280	310	295
First Fertilization Level	320	345	332.5
Second Fertilization Level	355	390	372.5
Third Fertilization Level	340	365	352.5
Treatment Means	323.75	352.5	
LSD	V:12.4	F:18.5	VXF:24.1

2. Number of Grains per Panicle (grains/panicle)

The statistical analysis showed that cultivar V2 produced a significantly higher number of grains per panicle than cultivar V1, with mean values of 55.77 and 49.25 grains panicle^{-1}, respectively, exceeding the least significant difference (LSD) value (Table 3). The superior performance of V2 can be attributed to its genetic characteristics, particularly its panicle architecture. This cultivar developed larger and more highly branched panicles, providing greater capacity for spikelet and floret development, which ultimately increased the number of grains formed after successful pollination.

Foliar application of micronutrients also had a significant effect on grain number per panicle. The F2 treatment recorded the highest mean (59.0 grains panicle^{-1}), whereas the control treatment (F0) produced the lowest mean (45.2 grains panicle^{-1}), with differences exceeding the LSD value of 3.4. This improvement is likely associated with the essential physiological functions of boron and zinc. Boron plays a critical role in pollen germination and pollen tube growth, thereby enhancing fertilization and reducing floret sterility. In addition, zinc supports enzyme activity and metabolic processes involved in reproductive development, while the combined availability of micronutrients improves the nutritional status of the plant, promoting embryo development and reducing grain abortion. These physiological processes contribute to improved grain set and a greater number of grains per panicle (Marschner, 2012).

The interaction between cultivar and micronutrient application was not significant for this trait, indicating that both cultivars responded similarly to foliar micronutrient application. Although V2 consistently produced more grains per panicle than V1, the magnitude of the response to micronutrient fertilization was comparable in both cultivars. This finding

suggests that the beneficial effects of micronutrient application on grain formation were largely independent of cultivar and reflected a similar physiological response under improved nutrient availability.

Table (3) Effect of micronutrients, cultivars, and their interaction on the number of grains per Tiller

Foliar Fertilization Levels	First Cultivar	Second Cultivar	Fertilization Means
Control	42.1	48.3	45.2
First Fertilization Level	48.6	54.0	51.3
Second Fertilization Level	55.3	62.7	54.0
Third Fertilization Level	51.0	58.1	54.55
Treatment Means	49.25	55.77	
LSD	V:2.1	3.4	VXF N.S

3. 1000-Grain Weight (g)

The statistical results in Table 4 demonstrated that Cultivar (V2) achieved a significant superiority, recording a 1000-grain weight of 33.4 g compared to 31.85 g for Cultivar (V1), with the observed variance exceeding the Least Significant Difference value. This divergence is fundamentally ascribed to genetic variation regarding the nutrient-sinking capacity of both cultivars. Cultivar V2 exhibits higher efficiency in translocation of stored photo-assimilates from the leaves and stems (the source) and partitioning them more rapidly and efficiently into the developing grains (the sink) during the grain-filling stage, thereby increasing grain density and ultimate size.

Foliar application of micronutrients also induced pronounced significant differences; the (F2) treatment level yielded the highest grain weight at 35.35 g, significantly outperforming the control (F0), which recorded 29.35 g, with a difference surpassing the LSD threshold of 1.25. This outcome can be explained by the role of micronutrients in prolonging the actual grain-filling period through delaying leaf senescence (the stay-green effect). Within this physiological mechanism, zinc (Zn) and manganese (Mn) act as potent antioxidants that protect foliar cells from degradation. Sustaining photosynthetic efficiency for an extended duration ensures a continuous influx of carbohydrates toward the growing grains, markedly improving their filling capacity and final weight. Furthermore, the two-way interaction exerted a statistically significant effect where the combination of V2 F2 registered the highest 1000-grain weight at 36.1 g. This significant interaction confirms that Cultivar 2 possesses a robust sink capacity and strong metabolic sinks that responded with exceptional efficiency to the nutrient abundance provided by the F2 foliar treatment. Consequently, this synergistic interplay facilitated complete and optimal filling of the grain storage reserves in V2 compared to Cultivar.

Table (4) Effect of micronutrients, cultivars, and their interaction on 1000-grain weight

Foliar Fertilization Levels	First Cultivar	Second Cultivar	Fertilization Means
Control	28.5	30.2	29.35
First Fertilization Level	31.2	32.8	32.0
Second Fertilization Level	34.6	36.6	35.35
Third Fertilization Level	33.1	34.5	33.8
Treatment Means	31.85	33.4	
LSD	V: 0.15	F1.25	FXV 2.20

4. Total Grain Yield (ton/ha^{-1}) This result was consistent with

The results revealed significant differences in total grain yield between the two evaluated cultivars (Table 5). Cultivar (V2) significantly surpassed Cultivar (V1), securing the highest mean yield of 4.21 ton/ ha^{-1} representing a 13.17% increase

over V1, which recorded a mean of 3.72 ton/ha^{-1}. This yield variance exceeded the Least Significant Difference threshold ton /ha^{-1}. Grain yield is inherently a complex quantitative trait governed by genetic architecture and its dynamic interaction with environmental factors. The productivity advantage of V2 can be credited to its proficiency in translating its aforementioned physiological superiority into substantial yield components. Genetically, this cultivar was characterized by a higher panicle density (352.5 m^2), a greater grain count per panicle 55.77 and an increased grain weight (1000-grain weight = 33.4 g). This structural integration among yield attributes, augmented by a robust vegetative canopy development and dry matter accumulation (biological yield), and ultimately maximized the total grain yield in favor of cultivar 2. This result was consistent with (Al-Nasr-Allah and Alhasany, 2025).

Foliar application of micronutrients significantly increased total grain yield, with the response improving as fertilization levels increased up to the F2 treatment. The F2 treatment achieved the highest productivity at 4.57 ton/ha^{-1}, significantly outperforming the control (F0), which yielded the minimum output of 3.27 ton /ha^{-1}. Conversely, elevating the micronutrient concentration to the third level (F3) resulted in a significant yield reduction compared to F2, dropping to 4.15 ton \ ha^{-1}. The scientific rationale for the yield enhancement via foliar feeding lies in the complementary and synergistic role of micronutrients (iron, zinc, manganese, and boron) in upgrading the plant's assimilation capacity. Foliar spraying delivered these essential elements directly to the canopy during critical growth phases, thereby: increasing chlorophyll content and photosynthetic efficiency (driven by Fe and Mn); stimulating cell division and auxin biosynthesis, which expanded productive tillering and panicle numbers (driven by Zn); and optimizing pollination, fertilization, and grain setting processes while minimizing floret sterility (driven by B). Collectively, these factors positively reverberated across the overall yield components. Conversely, the yield decline observed at the F3 level is physiologically driven by mild toxicity or an ionic imbalance within the plant cytoplasm, which suppresses certain vital metabolic pathways, adversely affects the grain-filling process, and consequently diminishes the final yield (Broadley *et al*., 2012; Tripathi *et al*., 2015).

Furthermore, the two-way interaction between the cultivars and fertilization levels exerted a highly significant effect on total grain yield ton/ha^{-1}), with the V2/times F2 interaction treatment registering the absolute highest grain yield at 4.90 ton/ ha^{-1}. This significant interaction confirms a plastic and superior genetic responsiveness of Cultivar 2 toward the foliar nutrition provided at the F2 level. This result indicates that V2 possesses a high sink capacity that enabled it to exploit the available nutrient abundance and elevated photosynthetic rates induced by fertilization. This ass*et al*lowed the cultivar to partition photo assimilates with exceptional harvest efficiency into economic grain yield, outperforming Cultivar 1 under identical environmental conditions (Fageria and Nascente, 2024).

Table (5) Effect of micronutrients, cultivars, and their interaction on grain yield

Foliar Fertilization Levels	First Cultivar	Second Cultivar	Fertilization Means
Control	3.10	3.45	3.27
First Fertilization Level	3.65	4.10	3.87
Second Fertilization Level	4.25	4.90	4.57
Third Fertilization Level	3.90	4.40	4.15
Treatment Means	3.72	4.21	
LSD	V:0.18	F: 0.24	VXF:0.52

5. Biological Yield (ton/ha^{-1})

The experimental data in Table 6 indicated a significant superiority of Cultivar (V2), which produced the highest mean biological yield of 10.35 ton/ha^{-1} marking a 10.11% increase compared to Cultivar 1 (V1), which recorded 9.40 ton/ha^{-1}. This observed variance exceeded the Least Significant Difference threshold (LSD = 0.35 ton/ha^{-1}. This production

advantage of V2 is fundamentally driven by its unique genetic architecture, which endows it with enhanced efficiency in vegetative growth and an expanded leaf area index. Consequently, this structural adaptation optimized solar radiation interception and upregulated the net photosynthetic rate, thereby promoting a positive accumulation of total plant dry matter.

Regarding the impact of micronutrient foliar fertilization, the application prompted a steady, significant increase in biological yield up to the second treatment level (F2). The F2 level achieved the maximum biological productivity at 11.02 ton/ha^{-1}, significantly outperforming the control treatment (F0), which registered the minimum biological yield of 8.50 ton/ ha^{-1}. Conversely, the F3 level induced a slight, statistically non-significant decline compared to F2, with the yield reaching 10.32 ton/ha^{-1}. This enhancement is deeply rooted in the vital physiological roles of the applied micronutrients; iron (Fe) is directly incorporated into chlorophyll biosynthesis and the photosynthetic electron transport chain, while zinc (Zn) remains indispensable for the synthesis of tryptophan the metabolic precursor of the growth auxin indole-3-acetic acid (IAA). Meanwhile, manganese (Mn) functions as an essential cofactor for the water-splitting enzyme s during photosynthesis. This physiological synergy collectively stimulated cell elongation and increased vegetative branching (tillering), thereby maximizing total biomass accumulation. Conversely, the minor decline observed at the F3 level can be explained by the onset of a nutrient imbalance within plant tissues or an approach toward cellular toxicity thresholds. Furthermore, the two-way interaction (V x F) exerted a statistically significant effect, where the combination of cultivar 2 with the second fertilization level (V2) registered the absolute highest biological yield at 11.65 ton/ha^{-1}. This significant interaction verifies the plastic and highly responsive nature of V2 toward increasing micronutrient concentrations. It further demonstrates that this cultivar possesses robust assimilatory capacity and efficient internal translocation mechanisms, allowing it to fully exploit the extra foliar nutrition and efficiently partition it into vegetative and structural biomass.

Table (6) Effect of micronutrients, cultivars, and their interaction on biological yield

Foliar Fertilization Levels	First Cultivar	Second Cultivar	Fertilization Means
Control	8.15	8.85	8.50
First Fertilization Level	9.20	10.10	9.65
Second Fertilization Level	10.40	11.65	11.02
Third Fertilization Level	9.85	10.80	10.32
Treatment Means	9.40	10.35	
LSD	V:0.35	F:0.48	VXF=0.80

6. Harvest Index (%)

The results revealed significant differences in harvest index between the two evaluated cultivars (Table 7). Cultivar V2 significantly outperformed cultivar V1, recording a higher mean harvest index of 40.59% compared with 39.54% for V1, with the difference exceeding the least significant difference (LSD) value. The superior performance of V2 may be attributed to its greater genetic potential for efficient dry matter partitioning. In addition to producing vigorous vegetative growth, V2 exhibited a higher capacity to translocate photo-assimilates from the source tissues (leaves and stems) to the developing grains (the sink) during the grain-filling period. This more efficient assimilate partitioning contributed to the higher harvest index observed in this cultivar.

Foliar application of micronutrients also significantly influenced harvest index values. The F2 treatment level significantly surpassed the control (F0), yielding the highest value of 41.46%, whereas F0 recorded the minimum value of 38.51%. This increment can be attributed to the fact that micronutrient foliar feeding not only promotes vegetative growth but also directly enhances yield components (grain number and weight). This was achieved through the roles of boron (B)

and zinc in boosting pollen grain viability, optimizing fertilization, and establishing robust metabolic sinks that draw photo-assimilates. Consequently, this mechanism upregulated the plant's translocation efficiency and maximized the harvest index. The interaction between cultivar and fertilization level had no significant effect on this trait. The absence of a significant interaction indicates that both cultivars responded similarly to the different foliar micronutrient treatments. Increasing micronutrient application improved dry matter partitioning toward the grains in both cultivars, and the magnitude of this response was comparable across cultivars. These findings suggest that the effect of foliar micronutrient application on harvest index was consistent regardless of cultivar.

Table (7) Effect of micronutrients, cultivars, and their interaction on harvest index

Foliar Fertilization Levels	First Cultivar	Second Cultivar	Fertilization Means
Control	38.04	30.98	38.51
First Fertilization Level	39.67	40.59	40.13
Second Fertilization Level	40.87	42.06	41.46
Third Fertilization Level	39.59	40.74	40.16
Treatment Means	39.54	40.59	
LSD	V:0.65	F:0.92	N.S

CONCLUSIONS

Cultivar Shifa (V2) demonstrated superior performance in growth and yield-related traits, resulting in the highest grain and biological yields under the F2 foliar micronutrient treatment. In contrast, the F3 treatment was associated with a decline in yield, which may be attributed to nutrient imbalance or mild toxic effects resulting from excessive micronutrient application.

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