Effects of different Boron and Zinc Fertilizers and their interaction on Boron Availability in Rhizosphere soil , Growth and Yield of Maize (Zea mays L.).

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Abstract

A field experiment was conducted in an agricultural field during the autumn season of 2025 to investigate the effects of nano and chelated fertilizers, including chelated zinc and boric acid, on boron availability in the rhizosphere and non-rhizosphere soils during two plant growth periods 70 and 100 days after sowing. The experiment was arranged according to a Randomized Complete Block Design RCBD. The treatments included a single application rate of nano-boron fertilizer 1 kg ha^{-1} and boric acid fertilizer 1 kg ha^{-1}, and maize seeds *Zea mays* L. were sown in the field on August 28, 2025. The results showed that the highest available boron concentration was recorded under the boric acid treatment, reaching 1.003 and 1.115 mg kg^{-1} in the rhizosphere and non-rhizosphere soils, respectively, at 70 days after sowing. At 100 days after sowing, the corresponding concentrations were 1.368 and 1.307 mg kg^{-1}, respectively. The results also indicated that the highest total boron concentrations in the shoot and root systems were recorded under the combined nano-fertilizer treatment nano-boron + nano-zinc, reaching 21.966 and 16.889 mg kg^{-1}, respectively, at 100 days after sowing.

Keywords: Rhizosphere, Chelated Zinc, Boric Acid, Available Boron, Nano-Fertilizers.

Introduction

Boron is one of the essential micronutrients required for plant growth and plays a fundamental role in several physiological processes. It is an important structural component of plant cell walls and contributes to the maintenance of cell wall integrity (15). In addition, boron is involved in photosynthesis, sugar transport, pollination, and fruit development. Boron deficiency can adversely affect chlorophyll content and photosynthetic activity, reduce nitrate reductase activity, and negatively influence fruit production. Plant boron requirements generally range from 10 to 100 mg kg^{-1}. Several studies have reported that the application of nanofertilizers can enhance plant growth, chlorophyll content, photosynthetic activity, total biomass production, and crop yield (21).

In recent years, several researchers have investigated the potential of nanotechnology to improve fertilizer-use efficiency. These efforts have led to the development and application of nanofertilizers, which are produced from organic and mineral materials and are generally considered compatible with plants and the environment. Nanofertilizers can enhance nutrient uptake efficiency while reducing nutrient toxicity and the excessive or inefficient use of mineral fertilizers (16). Compared with conventional fertilizers, nanofertilizers may provide greater efficiency because of their positive effects on food-crop quality, their application at relatively low rates, and their rapid uptake

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by plant roots, followed by their movement and utilization within plant tissues (18).

Boron is an essential micronutrient that occurs in soils primarily in the form of boric acid H_3 BO_4, adsorbed onto aluminum and iron oxides and the surfaces of clay minerals, and associated with soil organic matter. Its availability is influenced by soil type and soil acidity (11). Boron is relatively immobile within plants; consequently, toxicity symptoms generally appear on older leaves, whereas deficiency symptoms are commonly observed in newly developing tissues (2). In dicotyledonous plants, the boron concentration generally ranges from 20 to 60 mg kg^{-1}, whereas in monocotyledonous plants it ranges from 6 to 18 mg kg^{-1} (6).

Boron plays an important role in plant development, particularly in cell division and cell-wall formation. In arid and semi-arid regions, boron is susceptible to leaching, which may influence its distribution and availability in the soil profile (3). Consequently, higher boron concentrations are often observed in the surface horizons of soils in arid and semi-arid regions (12; 8).

Boron also plays a critical role in flowering, yield components, and maize grain productivity. The application of boron has been reported to positively influence maize ear development. In one study, boron fertilization at 4 kg ha^{-1} resulted in the highest ear weight 44.85 g and ear yield 7.48 t ha^{-1}(13). Furthermore, the foliar application of 15 kg zinc combined with 1.5% boron resulted in the highest number of grains per ear 523.93 and the highest grain yield 6.33 t ha^{-1} (14).

Materials and Methods

Experimental Site and Field Preparation

The experiment was conducted in an agricultural field located in Al-Nouriya village, Al-Qadisiyah Governorate, near the College of Agriculture, University of Al-Qadisiyah, Iraq. The experimental site was located at latitude 31.962823° N and longitude 44.779969° E. The experiment was conducted during the autumn growing season of 2025 in a clay-textured soil with an electrical conductivity EC of 2.53 dS m^{-1} and a pH of 7.69. The total area of the selected field was 250 m^2.

The field was prepared by carrying out the necessary agricultural operations, including plowing, harrowing, and leveling. Three main irrigation channels were established along the field, with secondary channels branching from them to serve the individual plots. The experimental area was divided into three blocks, with each block containing seven plots. Each plot measured 3 × 3 m and represented one experimental unit. A 1-m buffer space was maintained between the experimental units to minimize the movement of applied fertilizers and irrigation water between treatments.

Maize seeds *Zea mays* L. of the local cultivar ‘Buhuth’ were sown in rows on August 28, 2025. The distance between rows was 75 cm, while the distance between planting holes was 25 cm. Each plot consisted of five rows. Three seeds were planted per hole, and the seedlings were thinned to one plant per hole two weeks after emergence. Each plot contained 50 plants.

All fertilizer treatments were applied after sowing. The maize stem borer *Sesamia calica* was controlled using granular diazinon insecticide containing 10% active

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ingredient, applied to the growing points of the plants 35 days after emergence. Weeds were controlled manually through hoeing and hand weeding whenever they appeared. The experimental units were irrigated by surface irrigation using equal amounts of water at regular intervals according to crop water requirements.

Table (1) Some chemical and physical properties of the study soil after sowing.

Property	Vaiue		Unit
pH 1:1	7.69		-----
EC 1:1	2.53		dS m-**1**
CEC	22.13		c mol**c** kg -**1** soil
Soluble cations	15.24	Ca+2	m mol. L-1
	10.43	Mg+2	
	22.20	Na+1	
	1.58	K+1	
Soluble anions	23.00	Cl-1	m mol. L-1
	19.00	HCO3-1	
	15.10	SO4-2	
	Nill	CO3-2	
Carbonates	255		g Kg-1 soil
Organic matter O.M	4.65		
Znic Available	0.942		mg kg-1 soil
Znic Total	32.09		
Boron Available	0.361		
Boron Total	27.68		
Texture	Clayey		
Bulk density	1.33		Mg m-3
Soil separates	217.00	Sand	g kg-1 soil
	368.00	Silt	
	415.00	Clay	

Determination of Total Boron

Total boron was determined using the dry-ashing method according to (7). The resulting samples were analyzed using

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inductively coupled plasma ICP spectrometry.

Determination of Available Boron

Available boron was extracted using 0.05 M hydrochloric acid according to the method described by , as previously applied by (10). The boron concentration in the extracts was determined using inductively coupled plasma ICP spectrometry.

Experimental Design and Treatments

The experiment was arranged according to a Randomized Complete Block Design RCBD, comprising seven experimental treatments, including an untreated control, with three replicates per treatment. The treatments were randomly distributed among the experimental units, resulting in a total of 21 experimental units.

The treatments were as follows:

- **Control:** No fertilizer was applied.
- **Nano-boron fertilizer:** Applied at a rate of 1 kg ha^{-1}, according to the recommended fertilizer rate.
- **Boric acid fertilizer:** Applied at a rate of 1 kg ha^{-1}, according to the recommended fertilizer rate.
- **Nano-zinc fertilizer:** Applied at a rate of 2 kg ha^{-1}, according to the recommended fertilizer rate.
- **Chelated zinc fertilizer:** Applied at a rate of 2 kg ha^{-1}, according to the recommended fertilizer rate.
- **Nano-zinc + nano-boron:** Applied at a combined rate of 2 + 1 kg ha^{-1}, respectively, with each fertilizer applied at half of its recommended rate.
- **Chelated zinc + boric acid:** Applied at a combined rate of 2 + 1 kg ha^{-1}, respectively, with each fertilizer applied at half of its recommended rate.

Results and Discussion

Available Boron

Effect of Fertilizer Treatments on Available Boron Concentration in Soil at 70 Days after Sowing

Table 2 presents the effect of the studied fertilizer treatments on the concentration of available boron in the rhizosphere and non-rhizosphere soils at 70 days after sowing. The statistical analysis revealed significant differences among the treatments at the 0.05 probability level. In the non-rhizosphere soil, all fertilizer treatments significantly outperformed the control treatment. The highest available boron concentration was recorded under the boric acid treatment, reaching 1.115 mg kg^{-1}, whereas the

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control treatment recorded the lowest value 0.220 mg kg^{-1}. The boric acid + chelated zinc treatment resulted in an available boron concentration of 1.073 mg kg^{-1}, followed by the nano-boron treatment with 0.942 mg kg^{-1}. The nano-boron + nano-zinc treatment recorded 0.733 mg kg^{-1}, while the nano-zinc and chelated zinc treatments resulted in 0.338 and 0.454 mg kg^{-1}, respectively.

In the rhizosphere soil, no significant differences were observed among the treatments, except for the boric acid treatment, which recorded a significantly higher available boron concentration than the control, reaching 1.003 mg kg^{-1}. This response may be attributed to the slightly alkaline soil pH 7.69; Table 2, which influences the chemical form and availability of boron in the soil. Under these conditions, boron may predominantly occur as boric acid, which is an important form of plant-available boron. This interpretation is consistent with the results obtained in the present study. The observed variation in available boron concentration may also be related to the interaction between boron and other soil constituents. Boron concentrations exceeding 4 mg kg^{-1} may cause toxicity to plants (5). In addition, the presence of calcium ions Ca^{2+} and the antagonistic relationship between calcium and boron may reduce boron uptake, particularly under relatively high soil pH conditions. In many cases, plants absorb boron primarily in the form of boric acid H_3 BO_4, which is the predominant boron species within a soil pH range of approximately 5–9.

Table 2. Boron Concentration mg kg^{-1} in Soil at 70 Days after Sowing

Treatments		**Outside rhizosphere region at 70 days**	**lnside rhizosphere region at 70 days**
Control	**T0**	0.220	0.454
Zinc Nano	**T1**	0.338	0.557
Boron Nano	**T2**	0.942	0.701
Zinc + Nano Boron Nano	**T3**	0.733	0.631
Zinc Chelated	**T4**	0.454	0.566
Boric acid	**T5**	1.115	1.003
Boric acid + **Zinc Chelated**	**T6**	1.073	0.735
L.S.D 0.05		**0.105**	**0.351**

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Effect of Fertilizer Treatments on Available Boron Concentration mg kg^{-1} at 100 Days after Sowing

Table 3 presents the effects of the studied fertilizer treatments on the concentration of available boron in rhizosphere and non-rhizosphere soils at 100 days after sowing. The statistical analysis revealed significant differences among the treatments at the 0.05 probability level. All fertilizer treatments significantly outperformed the control, except for the nano-zinc and chelated-zinc treatments, which did not differ significantly from the control.

The highest available boron concentrations in both the rhizosphere and non-rhizosphere soils were recorded under the boric acid treatment, reaching 1.368 and 1.307 mg kg^{-1}, respectively. In contrast, the control treatment recorded the lowest available boron concentrations, with values of 0.195 and 0.186 mg kg^{-1} in the rhizosphere and non-rhizosphere soils, respectively. The boric acid + chelated zinc treatment recorded available boron concentrations of 1.275 and 1.253 mg kg^{-1} in the rhizosphere and non-rhizosphere soils, respectively. The nano-boron treatment recorded values of 1.095 and 1.004 mg kg^{-1}, respectively, whereas the nano-boron + nano-zinc treatment resulted in concentrations of 0.937 and 0.769 mg kg^{-1}, respectively. The chelated-zinc treatment recorded 0.438 and 0.413 mg kg^{-1}, while the nano-zinc treatment resulted in 0.289 and 0.354 mg kg^{-1} in the rhizosphere and non-rhizosphere soils, respectively.

Table 3. Available Boron Concentration mg kg^{-1} in Soil at 100 Days after Sowing

Treatments		**Outside rhizosphere region at 100 days**	**lnside rhizosphere region at 100 days**
Control	**T0**	0.195	0.186
Zinc Nano	**T1**	0.289	0.354
Boron Nano	**T2**	1.095	1.004
Zinc + Nano Boron Nano	**T3**	0.937	0.769
Zinc Chelated	**T4**	0.438	0.413
Boric acid	**T5**	1.368	1.307
Boric acid + **Zinc Chelated**	**T6**	1.275	1.253
L.S.D 0.05		**0.338**	**0.419**

(1) reported that organic residues undergo decomposition over time, releasing dissolved organic carbon and causing the breakdown of carbon associated with negatively charged functional groups. These groups tend to interact with positively charged ions of micronutrients, thereby influencing their availability in the soil. The results presented in Table 3 showed that the boric acid treatment and the boric acid + chelated zinc treatment outperformed the nano-boron and nano-boron + nano-zinc treatments, respectively. This finding highlights the important role of boric acid in maintaining boron availability toward the end of the growing season and in contributing to the sustainability of soil boron supply. The addition of either nano-zinc or chelated zinc increased boron availability in the soil compared with the control; however, the differences between the zinc treatments were not significant.

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This response may be related to the positive effect of zinc on plant growth and nutrient uptake. However, the presence of zinc may also have influenced boron availability in the soil. This interpretation is supported by the lower boron concentrations recorded under the combined nano-boron + nano-zinc and boric acid + chelated zinc treatments compared with the individual nano-boron and boric acid treatments, respectively, in both rhizosphere and non-rhizosphere soils

Effect of Fertilizer Treatments on Total Boron Concentration mg kg^{-1} in the Shoot and Root Systems at 100 Days after Sowing

Table 4 presents the effects of the studied fertilizer treatments on the total boron concentration in the shoot and root systems of maize plants. The statistical analysis revealed significant differences among the treatments at the 0.05 probability level. All fertilizer treatments significantly outperformed the control treatment. The highest total boron concentrations in both the shoot and root systems were recorded under the nano-boron + nano-zinc treatment, reaching 21.966 and 16.889 mg kg^{-1}, respectively. In contrast, the control treatment recorded the lowest boron concentrations, with values of 5.712 and 6.636 mg kg^{-1} in the shoot and root systems, respectively. The boric acid + chelated zinc treatment resulted in boron concentrations of 19.682 and 15.365 mg kg^{-1} in the shoot and root systems, respectively. The nano-boron treatment recorded values of 18.445 and 13.781 mg kg^{-1}, respectively, whereas the boric acid treatment resulted in concentrations of 16.246 and 12.960 mg kg^{-1}, respectively. The nano-zinc treatment recorded 6.624 and 7.362 mg kg^{-1}, while the chelated-zinc treatment resulted in 6.371 and 7.040 mg kg^{-1} in the shoot and root systems, respectively.

Table 4. Boron Concentration mg kg^{-1} dry matter in the Shoot and Root Systems at 100 Days after Sowing

Treatments		**Boron concentration in shoot**	**Boron concentration in root**
Control	**T0**	5.712	6.636
Zinc Nano	**T1**	6.624	7.362
Boron Nano	**T2**	18.445	13.781
Zinc + Nano Boron Nano	**T3**	21.966	16.889
Zinc Chelated	**T4**	6.371	7.040

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Boric acid	**T5**	16.246	12.960
Boric acid + **Zinc Chelated**	**T6**	19.682	15.365
L.S.D 0.05		**1.139**	**0.671**

Significant differences were observed among most of the fertilizer treatments in both the shoot and root systems. However, the chelated-zinc treatment did not differ significantly from either the control or the nano-zinc treatment. This may be attributed, on the one hand, to the absence of boron in the composition of these treatments and, on the other hand, to the fact that the boron supplied to the plants originated primarily from the naturally available soil boron. The absence of significant differences from the control treatment further supports this interpretation. Boron plays a positive role in carbohydrate translocation and in protecting auxin and facilitating its transport. Consequently, it can promote cell division and cell expansion in growing tissues,. The results indicate that the nano-fertilizer combination (nano-boron + nano-zinc) and the chelated fertilizer combination (boric acid + chelated zinc) supplied greater amounts of boron to the shoot and root systems than the individual nano-boron and boric acid treatments, respectively.

Effect of Different Fertilizer Treatments on Maize Yield

Table 5 presents the effect of the different fertilizer treatments on maize yield weight. The statistical analysis revealed highly significant differences among the treatments at the 0.05 probability level. All fertilizer treatments significantly outperformed the control treatment, which recorded the lowest yield weight (146.40 g). The nano-boron + nano-zinc treatment (T3) recorded the highest yield weight, reaching 264.47 g, followed by the boric acid + chelated zinc treatment (T6), which recorded 252.44 g. The nano-zinc treatment (T1) resulted in a yield weight of 248.55 g, while the nano-boron treatment recorded 246.42 g. The chelated-zinc and boric acid treatments recorded 232.79 and 231.44 g, respectively.

Grain yield depends partly on the plant's ability to efficiently allocate assimilates and nutrients to reproductive organs (20; 19). Nanofertilizers, when used in combination with conventional fertilizers, can improve nutrient transport and consequently enhance crop productivity and grain yield. Nanoparticles smaller than 5 nm may enter leaves through stomata and subsequently

move through the vascular system. Their effectiveness may depend on their chemical composition and physical form, which can influence their behavior within plant tissues and ultimately affect biomass accumulation and yield (17).

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Table 5. Effect of Different Fertilizer Treatments on Maize Yield Weight kg ha⁻ ¹

Treatments		**Yield weight**
Control	**T0**	146.40
Zinc Nano	**T1**	248.55
Boron Nano	**T2**	246.42
Zinc + Nano Boron Nano	**T3**	264.47
Zinc Chelated	**T4**	232.79
Boric acid	**T5**	231.44
Boric acid + **Zinc Chelated**	**T6**	252.44
L.S.D 0.05		**3.122**

Conclusions

- The boric acid treatment and the boric acid + chelated zinc treatment resulted in the highest boron availability in the soil at both 70 and 100 days after sowing. In contrast, the nano-zinc + nano-boron treatment recorded the highest zinc availability during both growth periods.
- The application of fertilizer treatments increased the availability of both Zn and B, particularly in treatments containing these elements in their composition. The sole nano-zinc treatment was the most effective in increasing Zn availability as the growing period progressed, whereas the sole boric acid treatment was the most effective in increasing boron availability with increasing plant age

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