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Research Article

Influence of Soil-Delivered Micronutrients (Iron and Zinc) on Soybean (*Glycine max* (L.) Merr.) Agronomic Performance and Quality under the Ecological Conditions of Central Anatolia, Türkiye

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Abstract

This study was carried out over a two-year period to evaluate the effects of soil-supplied iron (Fe) and zinc (Zn) on the agronomic traits and quality of soybean (*Glycine max* L.) under the ecological conditions of Central Anatolia, Türkiye. The study utilized the early-maturing Atakişi cultivar, which is well-adapted to the Central Anatolian and Mediterranean regions. $FeSO_4 \cdot 7H_2O$ (1.5 kg/da) and $ZnSO_4 \cdot 7H_2O$ (3 kg/da) fertilizers were incorporated into the soil prior to sowing. A randomized complete block design was utilized in the study, comprising four treatments (Fe, Zn, Fe+Zn, and control) with four replications, resulting in a total of 16 plots. Key agronomic parameters (such as branch number per plant, plant height, first branch height, first pod height, pod number per plant, seeds per pod, pod length, 1000-seed weight, and yield per decare) were measured alongside quality traits, including protein, ash, and oil contents (%). The findings demonstrated that soil applications of Fe and Zn significantly affected plant height number of branches ($p<0.01$), ($p<0.05$), and pod length ($p<0.05$) throughout the study period, while the number of seeds per pod was significantly influenced by both the treatments ($p<0.01$) and the interaction between year and treatment. Other agronomic traits did not show significant responses to either the year or treatments ($p>0.05$). The Fe+Zn treatment resulted in the highest protein content (37.59%), the Fe treatment produced the highest oil content (19.80%), and the greatest ash content (9.10%) was observed in the Fe+Zn treatment during the second year. Overall, combined Fe and Zn applications enhanced both seed number and quality-related traits. It was concluded that such applications can significantly enhance yield and quality in soybean cultivation, especially on micronutrient-deficient, calcareous, and alkaline soils.

Türkiye'nin Orta Anadolu Ekolojik Koşullarında Topraktan Uygulanan Mikro Besin Elementlerinin (Demir ve Çinko) Soya Fasulyesinin (*Glycine max* (L.) Merr.) Agronomik Performansı ve Kalitesi Üzerindeki Etkisi

Özet

Bu çalışma, topraktan verilen demir (Fe) ve çinkonun (Zn) Türkiye'nin Orta Anadolu, Türkiye ekolojik koşullarında soya fasulyesi (Glycine max L.) üzerindeki agronomik özellikler ve kaliteye etkilerini değerlendirmek amacıyla iki yıl süreyle yürütülmüştür. Çalışmada, Orta Anadolu ve Akdeniz bölgelerine iyi adapte olmuş erken olgunlaşan Atakişi çeşidi kullanılmıştır. $FeSO_4·7H_2O$ (1,5 kg/da) ve $ZnSO_4·7H_2O$ (3 kg/da) gübreleri ekim öncesi toprağa karıştırılarak uygulanmıştır. Çalışmada, dört konu (Fe, Zn, Fe+Zn ve kontrol) ve dört tekerrürlü tesadüf blokları deneme deseni kullanılmış ve toplam 16 parselde yürütülmüştür. Tarımsal özellikler (bitki başına dal sayısı, bitki boyu, ilk dal boyu, ilk bakla boyu, bitki başına bakla sayısı, bakla başına tohum sayısı, bakla uzunluğu, 1000 tohum ağırlığı ve dekar başına verim) ile protein, kül ve yağ içeriği (%) gibi kalite özellikleri ölçülmüştür. Bulgular, topraktan uygulamalarda Fe ve Zn'un bitki boyu ($p<0,05$), dal sayısı ($p<0,01$) ve bakla uzunluğu ($p<0,05$) üzerinde yılın önemli etkileri olduğunu göstermiştir. Baklada dane sayısı ise hem uygulamalarda ($p<0,01$) hem de yıl × uygulama etkileşiminden önemli ölçüde etkilenmiştir. Diğer tarımsal özellikler, yıl veya uygulamalardan önemli ölçüde etkilenmemiştir ($p>0,05$). En yüksek protein içeriği Fe+Zn uygulamasının birinci yılında (%37,59), en yüksek yağ içeriği (%19,80) Fe uygulamasın ikinci yılında ve en yüksek kül içeriği (%9,10) ise ikinci yılın Fe+Zn uygulamasından gözlemlenmiştir. Genel olarak, Fe ve Zn'in birlikte uygulanması hem dane sayısını hem de kaliteyle ilgili özellikleri artırmıştır. Bu uygulamaların, özellikle mikro besin maddelerince eksik, kireçli ve alkalin topraklarda soya fasulyesi üretiminde verim ve kaliteyi önemli ölçüde artırabileceği sonucuna varılmıştır.

Anahtar Kelimeler
Soya fasulyesi, demir, çinko, kalite, verim.

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1. INTRODUCTION

Soybean (*Glycine max* L.) is a leguminous crop of global strategic significance due to its high protein content, substantial oil yield, and ability to fix atmospheric nitrogen. Beyond its contribution to human and animal nutrition, soybean serves as a major oilseed crop with various industrial applications, providing a valuable source of protein, oil, and bioactive compounds [12]. Furthermore, through symbiotic nitrogen fixation, soybean contributes to soil fertility, promoting sustainable agricultural systems [21];[31]. Achieving the full yield potential of soybean depends not only on adequate macro-nutrient supply but also on sufficient levels of micronutrients [23].

Deficiencies of micronutrients, particularly essential elements such as iron (Fe) and zinc (Zn), have direct impacts on plant growth and development, as they play vital roles in plant metabolic processes. Both elements are integral components of oxidoreductase enzymes and participate in essential physiological functions, including photosynthesis, respiration, nitrogen metabolism, and protein synthesis [1];[3]. Iron is crucial for chlorophyll biosynthesis and electron transport, whereas zinc is required for a variety of biochemical activities, such as cell division, auxin and protein synthesis, carbohydrate metabolism, and the regulation of antioxidant defense systems [1];[4];[5].

Deficiencies of Fe and Zn are especially prevalent in calcareous and high pH soils, where the reduced solubility of these micronutrients restricts their availability and uptake by plants [19]. Iron deficiency in legumes, often manifested as Iron Deficiency Chlorosis (IDC), can lead to reduced plant height, poor root development, decreased photosynthetic activity, and yield losses. Similarly, Zn deficiency reduces plant stress tolerance and negatively affects crop quality [5];[10];[24];[27]. Fertilizer form (sulfates, EDTA chelates, nano-formulations) and application rate are also key factors influencing Fe and Zn uptake by plants [7];[22]. Soil-applied micronutrient fertilization is a widely used method to mitigate these deficiencies and enhance nutrient uptake.

Previous research has demonstrated that soil applications of Fe and Zn positively influence soybean growth, yield, and quality-related traits, including plant height, leaf number, pod number, flowering time, and seed yield. Application of Fe mitigates chlorosis in calcareous and alkaline soils, thereby enhancing plant development and seed production, whereas Zn application promotes pod and seed numbers, 1000-seed weight, and protein content [4];[25]. Studies on optimal fertilization rates have shown that Zn doses of 5–10 kg ha^{-1} significantly increase pod and seed numbers, yield, protein content up to 40%, and oil content exceeding 20%, while $FeSO_4$ applications positively affect yield components and nutrient uptake [14];[15];[17].

Thus, micronutrient fertilization not only enhances crop yield but also improves product quality, including protein, oil, and mineral content [32]. However, antagonistic interactions between Fe and Zn have been reported. Excessive Zn can limit Fe uptake, exacerbating Fe deficiency, highlighting the importance of carefully planned micronutrient fertilization [2];[19]. This underscores the need to optimize dose, timing, and application strategy for effective micronutrient management.

Therefore, investigating the effects of soil-applied Fe and Zn on soybean agronomic traits (e.g., plant height, pod number, seed number, yield) and quality parameters (protein, oil, mineral contents) is of great importance. Particular attention should be given to interactions between application method (soil vs. foliar), dose, timing, and soil conditions.

The main aim of this research is to assess the impact of soil-applied iron (Fe) and zinc (Zn) fertilizers on the agronomic traits (such as plant height, yield, number of pods, and number of seeds) and quality attributes (including protein, oil, and ash content) of soybean (*Glycine max* L.). Both individual (Fe or Zn) and combined (Fe+Zn) applications are compared to assess potential synergistic or antagonistic interactions. Soil properties (e.g., pH, lime content, organic matter) influencing micronutrient uptake are also considered. The findings are expected to contribute to the development of optimized fertilization strategies, guide soybean producers in micronutrient management, and support sustainable production systems.

2. MATERIALS AND METHODS

This study was conducted over a two-year period under the unique ecological conditions of the Central Anatolia Region and aimed to investigate the effects of soil-applied iron (Fe) and zinc (Zn) micronutrients on the agronomic traits and quality parameters of soybean (*Glycine max* L.).

In the experiment, the medium early Atakişi soybean variety developed in Türkiye and adapted to both Central Anatolia and Mediterranean ecologies was used as the plant material. The field trials were carried out in the experimental plots of Selçuk University Sarayönü Vocational School, located in the Sarayönü district of Konya province in the Central Anatolia Region of Türkiye. The experimental site is situated at an elevation of 1055 m above sea level.

2.1. Soil and Climate Characteristics

The soil of the experimental area was characterized as clay-loam in texture, slightly alkaline (pH 7.75), slightly saline (E.C. 4.34 mS/cm), with a moderate organic matter content (2.35%) and high lime content (18.91%) (Table 1). Due to their high pH and lime content, such soils represent typical problematic agricultural lands where the solubility of micronutrients such as zinc and iron decreases, thereby limiting their uptake by plants [20]. These conditions elevate the risk of Iron Deficiency Chlorosis (IDC) in legumes, negatively affecting plant growth [24]; [27]. Soil structure and fertility are particularly critical for nutrient uptake and nodule formation in soybeans [11].

Table 1. *Some physical and chemical properties of the experimental soil*

Soil Property	Value
Texture	Clay loam
pH	7.75
E.C. (mS/cm)	4.34
Lime (%)	18.91
Organic Matter (%)	2.35
Available P (kg da^{-1})	6.3
Available K (kg da^{-1})	201.6

Monthly mean maximum, minimum, and average temperatures, along with precipitation data for the region where the experiment was conducted, were obtained from the TİGEM Gözlü Agricultural Enterprise Meteorology Station (Table 2).

An examination of the climatic parameters indicated that average maximum, average, and minimum temperatures as well as precipitation levels during the experiment were generally more favorable in the second year compared to the first. These climatic differences are expected to have significant effects on morphological characteristics such as plant height [35] and pod development [34], as soybean is particularly sensitive to environmental conditions during flowering and pod-setting stages [30].

Table 2. *Meteorological data of the trial site*

Meteorological parameters	*Years*	*Months*											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly maximum temperature averages (°C)	1 st year	10.3	7.5	26.6	31.0	30.5	34.3	36.8	36.1	32.4	24.0	19.0	16.6
	2 st year	13.1	14.7	19.5	21.2	29.6	33.3	34.6	34.4	31.2	27.6	19.8	16.4
	Long-term averages	4.7	6.8	12.0	17.4	22.2	26.8	30.2	30.0	26.1	20.0	13.0	6.7
Monthly temperature averages (°C)	1 st year	-3.8	3.2	9.0	12.9	14.5	20.9	23.2	24.4	18.6	11.4	7.3	0.5
	2 st year	1.7	3.3	4.2	9.4	21.4	20.3	31.0	24.9	12.3	15.0	6.2	4.9
	Long-term averages	-0.2	1.2	5.7	11.0	15.7	20.2	23.6	23.0	18.6	12.5	6.1	1.8
Monthly temperature averages (°C)	1 st year	14.0	16.0	-5.2	-0.4	-0.9	7.1	11.0	12.4	4.3	0.2	-4.8	-18.6
	2 st year	-19.0	-8.4	-6.7	-4.0	3.6	7.3	11.2	6.8	2.0	0.7	5.7	-4.7
	Long-term averages	-4.1	-3.3	0.0	4.5	8.6	12.9	16.2	15.7	11.2	6.1	0.8	-2.2
***Rainfall* (mm)**	1 st year	5.8	20.6	11.4	11.1	5.9	13.5	6.0	0	48.2	30.4	36.0	54.0
	2 st year	41.4	23.9	22.0	32.7	48.5	6.0	20.7	0	8.5	27.1	24.8	18.0

	Long-term averages	35.3	28.2	27.1	34.0	43.6	23.2	6.9	5.6	11.2	31.3	33.1	44.8

Source: *TİGEM (Gözlü Agricultural Enterprise Directorate) meteorological station – DMGM data*

2.2. Experimental Design and Cultural Practices

The research was conducted using a Randomized Complete Block Design (RCBD) with four replications and four treatments, totaling 16 plots, in order to minimize environmental variation. Each plot was 5 m in length and consisted of four rows. Sowing was performed manually with a row spacing of 40 cm and an intra-row spacing of 5 cm [18]. This planting density was selected considering its effects on plant growth and yield components [26].

The treatments were as follows:

1. Control (no fertilizer applied)
2. Fe (Iron sulfate application)
3. Zn (Zinc sulfate application)
4. Fe + Zn (Combined iron and zinc sulfate application)

Along with sowing, 15 kg/da of DAP (18–46-0) fertilizer was applied. As micronutrient sources, 1.5 kg/da $FeSO_4 \cdot 7H_2O$ and 3 kg/da $ZnSO_4 \cdot 7H_2O$ were used, and the entire amount of these fertilizers was incorporated into the soil before sowing. Soil application is a common and effective method for correcting micronutrient deficiencies [22], particularly important in calcareous soils where nutrient uptake is often restricted [1]. To support the biological nitrogen fixation capability of soybean, seeds were inoculated with *Rhizobium* bacteria prior to sowing [13]. This symbiotic nitrogen fixation enhances soil fertility, which is critically important for sustainable agriculture [21];[32]. Sowing dates were May 19 in the first year and May 12 in the second year; harvests were carried out on October 27 and November 3, respectively. Throughout the growing season, irrigation was performed six times using a drip irrigation system, each for a duration of five hours [6]. Weed control was carried out mechanically.

To minimize border effects, the first and last rows of each plot were excluded from measurements and observations.

2.3. Measured Agronomic and Quality Traits

Agronomic traits were evaluated based on the INTSOY (International Soybean Program) methodology. The measured traits included plant height (PH), number of branches per plant (BNP), number of pods per plant (PNP), first pod height (FPH), pod length (PL), number of seeds per pod (SPP), first branch height (FBH), 1000 seed weight (1000SW), and seed yield per decare (GY) all important yield components and morphological parameters [9].

Additionally, quality traits such as protein, ash, and oil contents (%) which are important in terms of soybean's nutritional value were analyzed. It is well known that micronutrients contribute not only to yield enhancement but also to improvements in seed protein, oil, and mineral contents [31].

2.5. Statistical Analysis

Statistical analyses of the collected data were performed using JMP software. Analysis of Variance (ANOVA) was used to examine the effects of treatments (Fe, Zn, Fe+Zn, Control) and year on the measured traits. Statistical significance levels were set at $p < 0.05$ (significant) and p < 0.01 (highly significant). When differences were found to be significant, comparisons were performed using the LSD test [33].

3. RESULTS AND DISCUSSION

This research was carried out over a two-year period under the ecological conditions of Central Anatolia to investigate the impact of soil-applied iron (Fe) and zinc (Zn) fertilizers on selected agronomic traits and quality attributes of soybean (*Glycine max* L.). The findings from the analysis of variance (ANOVA) are presented in Table 3, whereas the yearly average values are provided in Table 4.

Table 3. *Effect of Treatments on Agronomic Characteristics*

PARAMETERS	PH	BNP	PNP	FPH	PL	SPP	FBH	1000SW	GY
	F	F	F	F	F	F	F	F	F
Year	4.6524*	43.7134**	0.2707	9.2506	23.5734*	0.8242	5.0091	0.3178	0.1982
Treatment	0.6615	0.0818	0.0446	0.1956	1.6709	6.2174**	0.5135	2.1917	0.3504
Year × Treatment	0.8098	0.7075	0.8267	0.6264	0.4870	3.7130*	0.9039	0.3529	0.8674

* : P < 0.05
**: P< 0.01

Abbreviations: PH (Plant Height), BNP (Branch Number per Plant), PNP (Pod Number per Plant), FPH (First Pod Height), PL (Pod Length), SPP (Seeds per Pod), FBH (First Branch Height), 1000SW (1000-Seed Weight), GY (Grain Yield per Decare)

As shown in Tables 3 and 4, no statistically significant variation was observed among the treatments for plant height (PH), whereas significant differences were detected between years (p<0.05). The mean plant height was 66.90 cm in the first year and 93.72 cm in the second year, with the maximum value (110.13 cm) recorded in the Fe treatment during the second year. This increase can be attributed to more favorable temperature, moisture, and precipitation conditions in the second year. These results align with earlier research indicating that environmental conditions play a major role in determining plant height [35].

While no significant differences were detected among treatments for branch number per plant (BNP), year-to-year variation was highly significant (p<0.01). The highest average branch number (3.53 branches) was observed in the Fe treatment during the first year. The interaction between environmental factors and the genetic makeup of the plant in branch formation has been emphasized in several studies [1].

Pod number per plant (PNP) was not significantly affected by either year or treatment (p> 0.05). However, the highest value (38.18 pods) was recorded in Zn-treated plots in the second year. Zn can enhance enzymatic activities during flowering and fertilization, thereby supporting pod formation [11].

No significant differences were observed for first pod height (FPH) among years, treatments, or their interaction (p>0.05). Nevertheless, for mechanical harvesting purposes, this trait reached its highest values in the control (18.15 cm) and Fe-treated plots (17.58 cm) during the second year [16].

Pod length (PL) exhibited significant differences between years (p<0.05), whereas no significant effects of the treatments were observed. The maximum mean pod length (4.25 cm) was achieved in the Fe+Zn plots in the first year, while the minimum (3.63 cm) was noted in the Fe plots during the second year, illustrating the significant role of climate variability in pod development [34].

Table 4. *Yearly means of some agronomic traits and quality parameters of soybean as affected by treatments*

PARAMETERS	ANNUAL AVERAGE	APPLICATIONS			
		CONTROL	Fe	Zn	Fe+Zn
Plant Height (cm)	1	65.86	65.70	66.68	69.35
	2	86.40	110.13	87.95	90.40
Branch Number per Plant (count)	1	3.45	3.53	3.05	3.15
	2	1.58	1.23	1.83	1.53
Pod Number per Plant (count)	1	34.43	33.35	30.53	34.15
	2	32.10	34.73	38.18	34.35
First Pod Height (cm)	1	12.75	12.70	13.81	13.84
	2	18.15	17.58	17.55	17.43
Pod Length (cm)	1	4.18	4.14	4.16	4.25
	2	3.85	3.63	3.83	3.95
Seeds per Pod (count)	1	2.80	2.88	2.93	2.93
	2	2.85	2.63	2.93	3.00
First Branch Height (cm)	1	5.70	5.73	6.38	5.71
	2	4.30	5.00	4.60	5.38
1000-Seed Weight (g)	1	115.11	121.11	116.59	118.43
	2	115.40	119.10	115.60	114.65
Grain Yield (kg/da)	1	343.33	376.67	390.00	350.00
	2	370.80	395.35	353.30	404.00
Protein (%)	1	36.53	32.32	30.46	37.59
	2	31.30	32.08	32.21	32.30
Ash (%)	1	5.58	4.75	7.65	8.13
	2	5.83	5.16	5.35	9.10
Oil (%)	1	15.80	16.10	16.30	16.40
	2	18.90	19.80	18.80	18.80

Seed number per pod (SPP) was significantly affected by the treatments ($p<0.01$), and the year × treatment interaction was also significant ($p<0.05$). The highest mean seed number (2.96 seeds) was recorded under the Fe+Zn treatment, with the maximum value (3.00 seeds) observed in the second year. The co-application of iron and zinc is thought to have a synergistic influence on plant metabolic processes, consequently enhancing fertilization efficiency [5];[7].

First branch height (FBH) did not differ significantly among years, treatments, or their interaction. The greatest average first branch height (FBH) was measured in the Zn-applied plots during the first year (6.38 cm), whereas the lowest value was observed in the control plots in the second year (4.30 cm).

No statistically significant effects of year, treatment, or their interaction were observed on 1000-seed weight (1000SW) and grain yield per decare (GY). However, the highest mean yield (404.00 kg/da) was achieved in Fe+Zn-treated plots. Microelements are reported to affect yield components indirectly rather than directly influencing yield [36].

In terms of quality traits, the highest protein content (37.59%) was observed in plots treated with Fe+Zn during the first year, the maximum ash content (9.10%) was recorded in Fe+Zn-treated plots in the second year, and the greatest oil content (19.80%) was detected in plots receiving only Fe in the second year. These results suggest that Fe and Zn play regulatory roles in protein biosynthesis and lipid metabolism in plants [3];[29]. These findings are in agreement with [1], who highlighted the complementary functions of micronutrients in plant growth and productivity.

4. CONCLUSION

The study demonstrated that iron (Fe) and zinc (Zn) applications, particularly when applied in combination, improved pod number and quality traits in soybean. However, their effects on overall yield were limited, suggesting that micronutrients contribute more indirectly rather than directly to yield. The application of $FeSO_4$ (1.5 kg/da) in combination with $ZnSO_4$ (3 kg/da) has the potential to improve both the productivity and sustainability of soybean cultivation in soils exhibiting micronutrient deficiencies. Future research is recommended to include long-term studies encompassing different application methods, dosages, and soil conditions.

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