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Research Article

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The Role of Zinc in Plant Growth and Human Nutrition Amid Climate Change

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ABSTRACT

Since zinc (Zn) has significant effects on wheat (a major food source for human health) growth, plant production is related to grain Zn concentration and is indirectly related to biofortification and climate change mitigation. Turkish soils have a severe Zn deficiency, which directly affects human nutrition through wheat plants. Genotypic variation in tolerance to Zn deficiency is well understood and may be related to differences in root growth and morphology, as well as mycorrhizal dependency and atmospheric carbon fixation. Two greenhouse experiments were conducted to determine the effects of Zn addition on wheat genotypes and plant growth and carbon dioxide fixation on Zn-deficient soil from the Central Anatolia Region, using forty bread and fifteen durum wheat genotypes in the first (Sultanönü soil) and second (Çomaklı soil) experiments, respectively. Plants were grown with (+Zn: 10 mg Zn/kg soil) or without (-Zn) Zn application in a randomised design. Plant growth, particularly in durum wheat, was significantly depressed in the control plant (−Zn) grown in Sultanönü soil. Zinc application more than doubled shoot biomass on average. Bread wheats generally out-yielded durum under −Zn. Resistant bread types included Kırkpınar, Bezostaja, and Aslım (rye), whereas sensitive durum included Kızıltan, Ç.1252, and Kunduru. Similar genotype rankings were reproduced in Çomaklı soil, with varieties, Zn, and their interaction being highly significant. Durum wheat genotypes were more susceptible to Zn deficiency than bread wheat genotypes, and this was related to less root production in durum wheat compared to bread wheat. Arbuscular mycorrhizal (AM) infection levels were low and irregular across genotypes and Zn treatments in both soils. Across genotypes, +Zn consistently elevated levels of tissue C and levels of estimated plant fixed CO_2 relative to −Zn. In Sultanönü, −Zn Kunduru fixed ~8.84 g CO_2 kg^{-1} soil, whereas +Zn Kunduru fixed ~14.44 g CO_2 kg ^{1} soil. Ranges spanned ~16.6 to 36.0 g CO_2 kg^{-1} soil across genotypes, with Aslım (rye) among the highest. In Çomaklı, +Zn increased CO_2 fixation from ~1.4 to 4.4 and ~5.5 to 11.2 g CO_2 kg^{-1} soil depending on genotype. These patterns underscore a link between adequate Zn nutrition for human nutrition, biomass accrual, and carbon capture potential, which is essential for combating climate change.
Keywords: Mycorrhizae, wheat genotypes, rhizosphere, root length, shoot-root ratio

INTRODUCTION

Due to the scarcity of water resources and the infertility of the soil in Central Anatolia, all the land in the region has been abandoned by farmers. In this region, factors such as high lime and clay content, low organic matter, and the absence or disruption of soil structure contribute significantly to the occurrence of these problems. Additionally, the effects of soil chemistry on the uptake of microelements by plants, particularly low zinc levels, which can severely affect plant development, especially in wheat (Cakmak et al., 1996), are noteworthy. Zinc (Zn) deficiency is reported to be more prevalent in clayey, calcareous, alkaline, low in organic matter, structurally deteriorated, base-compacted, or high in phosphorus soils (Murphy and Walsh, 1972). Due to the high clay and lime content of the soils in the Inner Anatolia and Southeast Anatolia regions of Turkey, DTPA-extractable or plant-available Zn levels in these soils are well below critical values. Zinc (Zn) is a nutrient element with low soil mobility, and its uptake by plants depends on plant characteristics and environmental factors. Research has determined that the DTPA-extractable microelement levels, especially zinc, in the soils of this region are very low (Cakmak *et al.*, 1996). Some genotypes were found to be more resistant to Zn deficiency, while others were not, highlighting the importance of understanding the factors influencing wheat genotypes' sensitivity to Zn deficiency. The resistance of wheat genotypes to Zn deficiency may arise from differences in plant root structure.

The growth of plant roots and their surface area play a key role in Zn uptake. Due to the slow mobility of zinc in soil, mass flow is a highly restricted mechanism for its transport. Plant root growth and root surface area play a primary role in better utilisation of Zn than phosphorus. Well-developed root structures can penetrate deeper into the soil, allowing plants to better utilize nutrients. Plant development and growth are influenced by genetic traits and environmental factors. The results showed that breeding programs in the Great Plains of the United States produced genotypes that mainly were susceptible to zinc deficiency. In contrast, genotypes with greater tolerance to the condition originated in Türkiye and the Balkan countries. Differences in root morphology and plant adaptation mechanisms, such as symbiosis with mycorrhizal fungi and root secretions, enable plants to access soil nutrients under current conditions. Understanding root uptake mechanisms and the detailed rhizosphere mechanisms will primarily determine the Zn and other nutrients plants take up from the soil, especially when plant roots are infected with mycorrhiza (Tinker, 1986). According to Marschner (1993), differences in the sensitivity of plant species to Zn can be attributed to genetic changes (Schlegel et al., 1998), changes in rhizosphere pH, plant secretions, and plant infection with arbuscular mycorrhizal fungi (AM). However, no experiment has been reported that investigates the relationship between root growth, carbon leek, and Zn uptake under soil conditions to date.

Effects of Mycorrhiza on Zinc Uptake

Microorganism species that live symbiotically with plant roots can enhance Zn uptake from the soil. When mycorrhizal fungi well colonize plant roots, they play a decisive role in the uptake of P and Zn from the soil (Li et al., 1991). Although the function of mycorrhizal fungi in plant phosphorus nutrition is widely recognised by researchers, Ortas (2024) claim that plant genotypes may vary depending on mycorrhizal associations. Recent studies have also shown that when mycorrhizal fungi colonise plants, the phosphorus nutrition of plant genotypes changes (Baon et al., 1993). In a survey by Lambers et al. (2011), six clover genotypes inoculated with mycorrhiza showed significant differences in response to phosphorus application compared with non-inoculated conditions.

According to Marschner (1993), mycorrhiza-infected plants have higher Zn concentrations in their root-shoot systems compared to non-infected plants, and they are less sensitive to Zn deficiency than non-infected plants.

Several mechanisms, such as root growth, mycorrhizal inoculation, root exudates, and rhizosphere redox potential, are suggested as genotype responses to Zn deficiency. According to Graham and Rengel (1993), the responses of genotypes to Zn deficiency do not differ in terms of root growth in hydroponic studies; however, in soils with Zn deficiency, some genotypes produce a large number of fine roots (<0.3 mm), occupying a larger soil volume and utilizing Zn in the soil more efficiently than those producing fewer roots. Differences in root growth, morphology, or mycorrhizal infection may help explain how genotypes utilize Zn differently. Some genotypes, under Zn deficiency, allocate more photosynthetic products (carbohydrates) to the root zone to acquire more Zn, either by producing more root dry matter or by releasing them as root exudates, thereby increasing the solubility of Zn in the rhizosphere.

The Relationship Between Zinc Fertilization and Climate Change

As global warming affects soil zinc dynamics, targeted zinc fertilization becomes critical for maintaining crop health and yield stability. Plant photosynthesis depends directly on the absorption of atmospheric carbon dioxide and on biomass production. Since Zinc promotes plant growth, plant biomass naturally increases atmospheric carbon fixation. In this context, Zn, which affects plant health and development, indirectly contributes to reducing CO_2 concentration. CO_2 fixation is crucial for plant growth and soil health because it supports soil organisms, such as AMF, which obtain carbon from plant sugars. In other words, soil and plants both release and mitigate CO_2 into the atmosphere. Therefore, the absorption of CO_2 from the atmosphere is crucial for controlling climate change. Zinc fertilization, by increasing plant biomass production and retaining high levels of carbon in its tissues, could be a way to reduce atmospheric CO_2 concentrations. Additionally, studies show that mycorrhizal fungi are crucial for improving zinc absorption. Climate variables that affect soil microbial communities can influence symbiotic species that enhance nutrient absorption, particularly in zinc-deficient environments.

Selective uptake of Zn, which plays a crucial role in plant nutrition and development, by mycorrhizal fungi in the plant root system through natural mechanisms, will be an important agricultural strategy. Furthermore, high Zn concentrations in foods play a crucial role in human nutrition and health protection, as well as plant development. In many regions, nearly half of the food humans eat comes from wheat. Zn has significant impacts on humans, plants, and ecosystems. In this context, Zn's vital roles in plant protein and enzymes production and growth hormone production, as well as its ability to bind more carbohydrates to mitigate climate change, are also important. Zn fertilisation can also help ensure adequate Zn intake from wheat products in our daily diet in several ways. Among the various factors influencing sustainable agriculture, zinc (Zn)—a vital micronutrient—stands out due to its crucial role in plant growth, soil health, and human nutrition. Bolan *et al.* (2025) clearly state that Zinc (Zn) deficiency in soils and, consequently, in crops has become one of the most common micronutrient deficiencies worldwide, leading to a sharp drop in agricultural yields and nutritional quality, as well as detrimental effects on human and animal health.

This decline not only affects crop health but also threatens human nutrition, especially in Mediterranean basin countries that are heavily reliant on cereal staples. Because zinc is involved in many enzyme mechanisms in plant tissues, it also stimulates or controls the uptake of other nutrients, thereby indirectly affecting human health. Improved zinc nutrition in crops directly benefits human health by increasing zinc content in the food chain.

To determine whether AMF inoculation combined with calibrated Zn fertilization simultaneously biofortifies wheat grain with absorbable Zn and increases plant- and soil-level C retention, thereby offering a dual nutrition–climate co-benefit. Climate change, zinc nutrition, and human nutrition are interconnected through Zn's roles in several enzymatic reactions, photosynthesis, and protein production. Since many plant growth processes depend on AM inoculation, integrating arbuscular mycorrhizal fungi (AMF) inoculation with several wheat genotypes will increase wheat grain Zn concentration and dietary Zn bioavailability and enhance plant growth and net carbon capture via photosynthetic CO_2 assimilation and biomass accumulation. The effects of Zn addition on wheat genotypes, plant growth, and carbon dioxide fixation on Zn-deficient soil from the Central Anatolia Region were investigated in two greenhouse experiments.

MATERIALS AND METHODS

Soil:

Sultanönü and Çomaklı soils, common soil series from the Central Anatolian plain with low zinc content, were used as experimental materials. After drying and sieving through a 4 mm sieve, various physical, chemical, and biological properties of the soils were analysed in the Laboratory of the Department of Soil at Çukurova University, and the findings are presented in Table 1.

Experiment I

Experimental Design:

In the experiment, Sultanönü soil was treated with two doses of ZnSO4: 0 and 10 mg Zn/kg soil. Nitrogen (200 mg N kg/soil) was used in the experiment, with calcium ammonium nitrate ($CaNH_4NO_3$) as the nitrogen source (26%). Phosphorus (100 mg P kg of soil) was applied as triple superphosphate. These fertilisers were mixed into the soil before sowing. Each pot was filled with 1.5 kg of soil.

Plant:

Forty different varieties of bread wheat (Triticum aestivum) and durum wheat (Triticum turgidum ssp. durum), primarily used for making pasta, couscous, and semolina products, are commonly grown in the region. Durum wheat is tetraploid, meaning it has four sets of chromosomes (AABB genome). Bread wheat is hexaploid (six sets of chromosomes) and was planted with and without zinc (10 mg Zn kg/soil and 0 mg Zn kg/soil). Fifteen wheat seeds were planted in each pot, and a week after emergence, the total number of plants was thinned to 10 seedlings. Soil was irrigated daily with distilled water to reach field capacity. The pot experiment was designed as a factorial block with 40 genotypes × 2 Zn levels × 3 replicates.

Harvest and Measurements:

During the experiment, pots were changed and irrigated as needed. Also Benlate fugiside was used for disease preture. After 40 days of sowing, plants were harvested by cutting them 0.5 cm above the soil surface. After harvesting, plant roots were separated from the soil, washed thoroughly with tap water, then with distilled water, and finally dried. The washed plant roots were blotted with absorbent paper to remove excess water, and the fresh weight was recorded. To preserve the vitality of the washed plant roots for diagnosing root length and mycorrhizal infection, they were placed in a mixed solution of ethanol, glacial acetic acid, and formaldehyde in a ratio of 250:13:5 (Ortas, 1994).

Mycorrhizal Infection:

Root cleaning and staining were performed according to the method described by (Koske and Gemma, 1989). After thoroughly washing the plant roots and removing the dead ones, they were placed in a Petri dish and cut into 1 cm segments. After these steps, the cut roots were transferred to test tubes at 1 cm intervals. After boiling the roots as indicated by Koske and Gemma (1989), the boiled roots were transferred to a Petri dish. Delicate and fragile root tips were randomly distributed using forceps, and the roots were examined for mycorrhizal infection under a microscope at 40–60× magnification, according to the method described by Giovannetti and Mosse (1980).

Determination of Root Length:

After diagnosing root infection, the remaining roots preserved in the alcohol solution were removed from the medium, and their dimensions were determined using a transparent container measuring 30 x 15 x 3 cm with a 1 cm grid, as described in Tennant (1975). After counting the roots, the root length was determined using the formula $L = pNA/2H$.

Plant Analyses:

After drying the shoot and root parts of the plants at 75°C for 24 hours, their dry weights were measured.

The calculation of plant tissue C% was multiplied by the dry weight per 2 kg of soil production. Total carbon content was converted to CO2 fixation.

Statistical Analyses:

The research results were statistically evaluated using SAS (Statistical Analysis System). A two-way ANOVA test was applied for both experiments as a factorial treatment.

Table 1. Some Physical, Chemical and Biological Properties of Soils

Soils	*Texture (%)			NH_4	NO_3	P_2O_5	* pH	*Zn	*Organic	Mycorrhizae spores
	Sand	Silt	Clay	ppm		(kg/ha)		(ppm)	Matter (%)	(10 g soil)
Sultanönü	21	35	44	2.70	6.70	17.0	8.10	0.16	1.2	190-220
Çomaklı	23	29	48	3.76	10.6	66.0	8.00	0.13	3.4	145- 308

Experiment II

Experimental Design:

Fifteen different wheat varieties (previously assessed in Experiment I) were tested in Çomaklı soil with two zinc doses (0 and 10 mg Zn/kg soil as zinc $ZnSO_4$). The experimental design and applications were prepared and implemented as in Experiment I.

RESULTS AND DISCUSSION

Experiment I

Above-Ground Dry Matter Production:

According to the preliminary analysis of the experiment's findings, which involved forty wheat varieties in Sultanönü soil, the varieties showed significant differences in dry matter production. During plant development, distinct zinc deficiencies were observed in some varieties under Zn-deficient application. In durum wheat varieties, zinc deficiency was more severe compared to bread wheat varieties. Zinc application significantly increased yields of these varieties, providing more than a twofold increase over the control (Table 2). In the control and zinc applications, there were statistically significant differences among wheat genotypes. The differences in dry matter production among varieties without zinc application were less pronounced than in the same varieties with zinc application. This indicates the sensitivity of wheat varieties to zinc.

As seen in Table 2 and Figure 1, when wheat varieties were arranged from smallest to largest in terms of dry matter production by plants under -Zn application, durum wheat produced less dry matter and was placed at the top of Table 2. Figure 1 shows that the most sensitive durum wheat in terms of dry matter production was Kızıltan, Ç.1252, and Kunduru, which ranked at the top of the table.

Among durum wheat varieties, BDMM-19, which is more resistant to zinc deficiency, was less affected and ranked lower in the table. Similar results were obtained in nutrient solution under controlled environmental conditions, where Erenoglu et al. (1999) reported that cultivars such as BDME-10 were more susceptible to Zn deficiency, whereas the Bezostaja cultivar was less affected.

Bread wheat was more resistant to zinc deficiency in terms of dry matter production. This improvement is reflected in a higher yield. Among bread wheat, P. Niska, Bul-63-68-7, and Gerek were the least productive in terms of dry matter, ranking lower in the table. The most resistant bread wheat in terms of dry matter production was Kırkpınar, Bezostaja, and Aslım. In both cases, the P.Niska and Bul-63-68.7 wheat varieties without zinc application were identified as more sensitive than other wheat varieties in terms of the amount of dry matter they produced. These varieties were also identified as sensitive bread wheat in field trials (Cakmak, 2003). Aslım, a rye variety, produced the highest dry matter, yet it ranked at the bottom of the table due to other factors. Rye is highly resistant to zinc.

According to statistical analysis, wheat varieties, zinc application, and the interactions were found to be significant at the $P < 0.001$ level (Table 3).

Root Dry Matter Production:

Differences among wheat varieties in root growth varied between bread and durum wheat under both zinc- and zinc-free applications. The difference between varieties was more pronounced in zinc-free than in zinc applications. Bread wheat varieties exhibited better root growth than durum wheat.

When wheat genotypes were ranked according to their dry matter production under Zn application, durum wheat produced less root dry matter, placing itself at the top left of Figure 2. Similarly, under the +Zn application, varieties showed lower responses, placing them towards the middle of the figure. However, this distinction cannot be clearly separated from above-ground dry matter production.

The inability to precisely collect all roots during washing and to completely remove the remaining soil and dead tissues during cleaning may have resulted in root dry matter production for some varieties differing from their actual values. As a result, groups formed by sensitive wheat genotypes and resistant durum varieties cannot be clearly distinguished in terms of root dry matter production. However, wheat varieties showed a more consistent response to +Zn and -Zn applications, depending on their bread or durum characteristics. According to the analysis of variance, wheat varieties, zinc application, and their interactions were found to be significant at the $P < 0.0001$ level (Table 2).

Stem/Root Ratio

When all wheat varieties were ranked by stem/root ratio in pots without zinc application, durum wheat varieties had lower stem/root ratios than bread wheat, thereby distinguishing themselves in the table (Table 2). Bread wheat varieties had a higher stem/root ratio, which placed them towards the bottom of the table and indicated their differences. Generally, bread wheat ratios were higher than those of durum wheat. BDMM-19, less sensitive than most durum varieties, is positioned close to sensitive bread wheat and ranks last in the table. Similar results were reported by Schlegel et al. (1998), who found that the stem/root ratio of bread wheat was higher than that of durum wheat in hydroponics.

In the case of zinc application, it was observed that the stem/root ratios of some bread wheat varieties were slightly lower than those of durum wheat varieties. Generally, durum wheat varieties were in the middle of the table. However, most bread wheat varieties exhibited a significantly higher stem/root ratio. The stem/root ratio is a crucial parameter for plant nutrition and nutrient transport between roots and stems. The lower stem/root ratio in durum wheat may be attributed to most carbohydrate products formed through photosynthesis being used for root development. Durum wheat, being a more sensitive variety, might need to produce more roots to absorb nutrients from the soil. Consequently, the stem dry matter weight is lower in bread wheat.

Table 2. Effect of zinc application on shoot and root dry weight of wheat genotypes.

Wheat	Shoot Dry Weight (10 plants)				Root dry weight (10 plants)				Shoot /Root	
Genotypes	-Zn		+Zn		-Zn		+Zn		-Zn	+Zn
ES-84-16	2,62	±0,16	5,53	±0,72	2,38	±0,25	3,30	±0,79	1,10	1,67
ES-14	2,62	±0,16	5,53	±0,72	2,38	±0,25	3,30	±0,79	1,10	1,67
ES-90-11	3,17	±0,37	6,05	±0,56	2,34	±0,36	3,64	±0,55	1,36	1,66
P.NISKA	2,83	±0,57	6,13	±0,47	1,71	±0,51	3,24	±0,21	1,66	1,89
BUL-63-68-7	3,15	±0,40	6,16	±0,49	1,08	±0,14	3,06	±0,20	2,91	2,01
BDMM-19	3,07	±0,47	6,44	±0,12	2,08	±0,34	3,76	±0,35	1,47	1,71
ES.SBVD2-23	3,48	±0,74	6,53	±0,42	3,05	±0,29	3,59	±0,25	1,14	1,82
ES-90-14	3,50	±0,60	6,53	±0,46	1,76	±0,22	3,50	±0,09	1,99	1,86
ATAY	4,05	±0,83	6,61	±0,12	2,66	±0,47	3,55	±0,36	1,52	1,86
ÇAKMAK	2,87	±0,21	6,62	±0,55	2,01	±0,20	3,35	±0,49	1,43	1,98
KIZILTAN	2,00	±0,10	5,72	±0,33	1,82	±0,15	3,50	±0,44	1,10	1,64
ES.SBVD1-2	3,80	±0,40	6,76	±0,23	2,22	±0,12	3,24	±0,24	1,71	2,09
GEREK	3,09	±0,31	6,78	±0,13	2,05	±0,17	4,45	±0,45	1,50	1,52
Ç. 1252	2,35	±0,13	6,90	±1,01	1,63	±0,24	3,75	±0,46	1,44	1,84
KUNDURU	2,37	±0,47	5,96	±0,72	1,39	±0,34	3,63	±0,44	1,70	1,64
ZITAVKA	4,27	±0,75	6,97	±0,13	2,94	±0,07	3,91	±0,65	1,45	1,78
ES.SBVD2-22	3,49	±0,20	7,04	±1,68	2,76	±0,36	3,27	±0,34	1,26	2,15
ES.SBVD1-21	4,17	±0,33	7,08	±1,06	2,80	±0,03	3,83	±0,29	1,49	1,85
ES.SBVD1-22	4,44	±0,48	7,12	±0,16	2,92	±0,38	3,97	±0,30	1,52	1,79
DAĞDAŞ	3,34	±0,33	7,15	±0,44	2,76	±0,68	4,21	±0,18	1,21	1,70
PARTİZANKA	4,03	±0,52	7,21	±1,15	2,13	±0,23	3,25	±0,38	1,89	2,22
KIRAÇ	3,58	±0,16	7,27	±0,32	2,43	±0,07	4,58	±0,29	1,47	1,59
BDME-10	3,71	±0,55	7,41	±0,28	1,99	±0,28	3,81	±0,23	1,86	1,94
ES-90-3	2,37	±0,21	7,63	±0,23	1,80	±0,26	4,78	±0,42	1,31	1,60
SERTAK	3,27	±0,08	7,63	±0,83	2,74	±0,34	4,49	±0,56	1,19	1,70
BEZOSTAJA	4,73	±0,46	7,68	±0,39	2,85	±0,15	4,86	±0,19	1,66	1,58
YAYLA	3,33	±0,42	7,71	±0,46	2,14	±0,27	4,50	±0,09	1,56	1,72
ES-91-12	3,67	±0,06	7,72	±0,38	2,57	±0,23	4,69	±0,14	1,43	1,65
PRESTO	4,78	±0,57	7,81	±0,44	3,36	±0,06	3,82	±0,41	1,42	2,04
KATE-A	3,15	±0,78	8,04	±0,46	1,98	±0,69	4,60	±0,33	1,59	1,75
ES.SBVD2-8	3,83	±0,20	8,09	±0,35	1,80	±0,32	3,21	±0,42	2,13	2,52
ASLIM	7,91	±1,04	8,51	±0,54	4,42	±0,40	4,08	±0,59	1,79	2,09
KIRKPINAR	4,81	±0,59	8,65	±0,33	2,12	±0,17	3,61	±0,19	2,27	2,40
GÜN-91	3,76	±0,40	8,74	±0,43	2,20	±0,41	4,74	±0,43	1,71	1,84
ES-90-8.1	2,90	±0,30	8,81	±0,82	1,62	±0,05	3,77	±0,28	1,79	2,34
ES-90-1	3,91	±0,47	9,30	±0,48	2,22	±0,13	4,71	±0,18	1,76	1,97
WARIGAL 5RL	3,91	±0,10	9,41	±1,04	2,23	±0,21	3,33	±0,21	1,76	2,83
DAGGER	2,84	±0,21	9,50	±0,88	1,61	±0,09	3,04	±0,21	1,76	3,12
BOLAL	3,33	±0,84	9,57	±1,04	1,74	±0,65	4,67	±0,18	1,91	2,05
NIS-22	3,89	±0,10	9,93	±0,60	2,09	±0,16	3,94	±0,52	1,86	2,52

The stem/root ratio is also an important indicator of how well the plant utilises nutrients taken up from the soil. The results of Cakmak et al. (1996) indicate that Zn-deficient plants had lower shoot/root dry weight ratios than Zn-sufficient plants, particularly in genotypes of durum wheat. In our results, the root/shoot ratio is considered a significant factor in plant zinc nutrition.

Root Length:

Significant differences were observed among wheat genotypes in root length per plant. As seen in Table 3, durum wheat varieties had shorter root lengths in both -Zn and +Zn applications. Bread wheat varieties that produced more root dry matter also had longer root structures. Root length is an essential parameter for nutrient uptake, especially for slow mobile nutrients such as phosphorus and zinc. Often, there is a strong correlation between plant root length and nutrient uptake. Therefore, recent research has focused on using the root length parameter to model nutrient uptake and develop fertilisation programs. One of the goals of this experiment is to determine the differences in growth among varieties and the resulting differences in root growth and root length. Future experiments will provide a more accurate test of this hypothesis.

Mycorrhizal Infection:

No significant relationship was determined among wheat varieties in terms of mycorrhizal infection percentages (Table 3). In both zinc-free and zinc applications, plant roots were infected with mycorrhiza, but the infection did not show a regular pattern. Mycorrhizal infection is low. The exact reason for this is unknown, but the fungicides used against powdery mildew, a fungal disease due to high humidity and temperature in greenhouse conditions, may have negatively affected mycorrhizal formation.

Table 3. Effect of zinc application on wheat genotypes' root length and root colonization

Wheat	Shoot length (cm)				Root Colonization			
Genotypes	-Zn		+Zn		-Zn		+Zn	
ES-84-16	69,1	± 8,5	86,5	± 9,9	33	± 3	31	± 6
ES-14	70,2	± 6,4	124,4	± 10,2	25	± 2	32	± 6
ES-90-11	69,5	± 7,8	92,9	± 14,6	30	± 4	46	± 6
P.NISKA	68,2	± 7,2	118,1	± 10,7	28	± 3	34	± 5
BUL-63-68-7	65,4	± 7,2	70,2	± 9,7	28	± 3	30	± 6
BDMM-19	65,5	± 4,5	94,6	± 9,6	17	± 3	30	± 5
ES.SBVD2-23	71,6	± 7,9	104,4	± 10,7	30	± 3	34	± 5
ES-90-14	55,5	± 7,8	98,6	± 10,0	30	± 3	31	± 7
ATAY	80,3	± 7,6	134,7	± 12,8	29	± 3	40	± 5
ÇAKMAK	51,3	± 4,4	89,2	± 7,2	17	± 4	23	± 7
KIZILTAN	48,1	± 4,8	91,1	± 6,4	18	± 4	20	± 6
ES.SBVD1-2	84,5	± 10,4	103,5	± 12,7	40	± 7	40	± 6
GEREK	76,1	± 11,8	114,3	± 13,4	45	± 4	42	± 7
Ç. 1252	67,4	± 6,4	89,7	± 8,2	25	± 4	26	± 8
KUNDURU	60,2	± 6,8	77,3	± 12,4	26	± 2	39	± 5
ZITAVKA	67,5	± 5,6	80,1	± 10,7	22	± 3	34	± 6
ES.SBVD2-22	79,5	± 11,3	95,6	± 9,4	44	± 4	30	± 7
ES.SBVD1-21	49,3	± 4,1	71,5	± 8,0	16	± 3	25	± 6
ES.SBVD1-22	79,6	± 8,4	100,2	± 10,5	32	± 4	33	± 7
DAĞDAŞ	78,3	± 4,8	107,8	± 9,2	18	± 4	29	± 7
PARTİZANKA	60,2	± 7,8	79,9	± 5,7	30	± 2	18	± 5
KIRAÇ	79,9	± 7,2	111,3	± 10,7	28	± 3	34	± 6
BDME-10	86,3	± 9,2	136,0	± 14,3	35	± 8	45	± 6
ES-90-3	51,6	± 5,8	87,8	± 13,9	22	± 3	44	± 6
SERTAK	95,9	± 8,0	124,7	± 16,3	31	± 2	51	± 6
BEZOSTAJA	90,3	± 7,6	109,9	± 11,2	29	± 4	35	± 6
YAYLA	79,5	± 5,6	110,4	± 6,6	22	± 3	21	± 5
ES-91-12	85,2	± 6,0	131,2	± 8,2	23	± 3	26	± 6
PRESTO	71,5	± 8,4	114,2	± 9,2	32	± 3	29	± 5
KATE-A	89,6	± 3,2	135,2	± 7,1	12	± 3	22	± 5
ES.SBVD2-8	61,7	± 4,6	98,9	± 10,0	18	± 3	32	± 5
ASLIM	85,2	± 9,6	115,9	± 7,7	37	± 2	24	± 5
KIRKPINAR	67,7	± 9,2	110,3	± 15,0	36	± 3	47	± 6
GÜN-91	81,2	± 8,4	110,2	± 8,2	32	± 3	26	± 5
ES-90-8.1	70,8	± 7,2	101,1	± 12,3	28	± 3	39	± 6
ES-90-1	71,5	± 7,1	115,2	± 9,5	27	± 3	30	± 7
WARIGAL 5RL	62,0	± 3,0	78,6	± 12,4	12	± 3	39	± 5
DAGGER	62,4	± 4,2	73,2	± 12,0	16	± 4	38	± 7
BOLAL	85,2	± 6,8	113,8	± 9,2	26	± 4	29	± 6
NIS-22	79,7	± 9,6	118,2	± 10,2	37	± 6	32	± 6

Zinc Use Efficiency (-Zn/+Zn):

The ratio of the values produced by zinc-free plants to those produced by zinc plants, known as zinc use efficiency, is an important parameter in plant zinc nutrition and is used to analyse fundamental differences among plants. As previously mentioned, no clear difference was determined between durum and bread varieties in the analysis of stem, root dry matter production, root length, and mycorrhizal infection data (Figure 1).

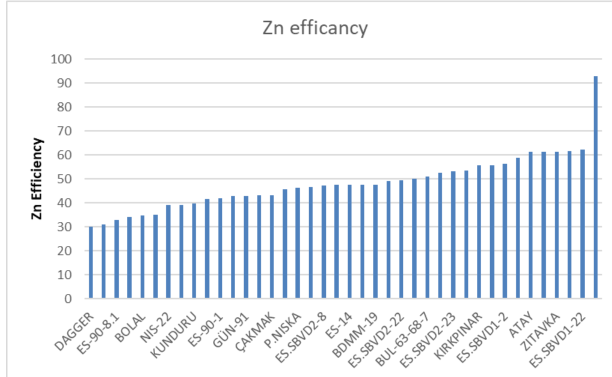

Figure 1. Zn efficiency of wheat genotypes in Sultanönü soil

Table 4. Effects of wheat genotype, carbon content and CO_2 fixation

	g C kg soil		g CO_2 kg soil		g CO_2 kg soil
Genotypes	(-Zn)	(+Zn)	(-Zn)	(+Zn)	(+Zn-(-Zn)
ES.SBVD1-2	1,80	2,72	6,59	9,98	3,40
BDME-10	1,77	2,92	6,47	10,71	4,24
ES-91-12	1,99	2,96	7,29	10,84	3,55
DAGGER	2,35	2,71	8,62	9,92	1,30
PRESTO	2,13	2,98	7,82	10,93	3,11
ES.SBVD1-22	2,35	2,77	8,62	10,14	1,52
Ç. 1252	1,87	3,42	6,87	12,55	5,68
BEZOSTAJA	2,29	3,24	8,40	11,89	3,49
KIZILTAN	2,59	3,00	9,50	11,01	1,51
SERTAK	2,42	3,19	8,86	11,68	2,82
PARTİZANKA	2,42	3,19	8,87	11,69	2,82
ES-14	1,96	3,66	7,18	13,42	6,24
GEREK	2,47	3,26	9,06	11,95	2,89
ATAY	3,07	3,10	11,26	11,37	0,11
ES.SBVD2-23	3,15	3,12	11,56	11,45	-0,12
ES.SBVD1-21	2,83	3,48	10,38	12,78	2,40
BUL-63-68-7	2,82	3,50	10,36	12,83	2,48
ES-90-3	2,89	3,45	10,61	12,64	2,03
YAYLA	2,87	3,48	10,51	12,76	2,25
KUNDURU	2,41	3,94	8,84	14,44	5,61
ÇAKMAK	2,68	3,70	9,84	13,58	3,75
ES.SBVD2-8	2,94	3,50	10,77	12,82	2,04
ES-90-1	2,12	4,31	7,79	15,81	8,03
ASLIM	2,64	3,83	9,70	14,03	4,33
ES.SBVD2-22	2,57	3,95	9,44	14,47	5,03
KIRKPINAR	2,83	3,71	10,36	13,59	3,22
WARIGAL 5RL	2,09	4,54	7,68	16,64	8,96
NIS-22	2,93	3,70	10,76	13,57	2,81
ES-90-11	3,28	3,44	12,03	12,61	0,59
ZITAVKA	3,39	3,40	12,42	12,46	0,05
ES-90-8.1	2,38	4,56	8,73	16,73	8,00
ES-84-16	2,80	4,24	10,27	15,56	5,28
P.NISKA	3,46	3,67	12,68	13,46	0,79
BOLAL	3,56	3,61	13,05	13,24	0,19
KATE-A	3,25	4,17	11,93	15,29	3,36
ES-90-14	2,89	4,57	10,58	16,76	6,17
DAĞDAŞ	2,88	4,61	10,56	16,91	6,35
KIRAÇ	2,81	4,75	10,29	17,41	7,12
BDMM-19	3,82	3,76	14,02	13,80	-0,22
GÜN-91	5,79	4,03	21,25	14,76	-6,49

Total Carbon Uptake and CO_2 Fixation

Total C content and CO2 fixation differed between genotypes. In general, Zn-applied genotypes have higher carbon contents than -Zn-treated genotypes. –Zn-treated BDME-10 genotype has shown a CO_2 content of 6.47 units (Table 4). The +Zn-treated BDME-10 genotype has 10.71 g of CO2. Total CO2 fixation ranged from 9.92 g CO2 per kg of soil to 16.64 g CO2 per kg of soil. The lowest CO2 fixed in Kızıltana mount of CO2 fixed was calculated in Kızıltan, while the highest g CO2 kg soil amount of grams of CO2 per kilogram of soil was found in the Aslım genotype. Differences between +Zn and –Zn are significant, demonstrating the efficacy of Zn application in mitigating the effects of CO2 concentration and carbon content on climate change.

Experiment II:

In this second experiment, 15 out of the 40 plant varieties previously included in the study were tested in the Çomaklı soil series, which is another common soil series in the Konya region with higher boron content. This research aimed to identify potential similarities in another soil condition, while accounting for differences that may arise from the data obtained in Experiment I. The soil in question is from the same region but has a higher boron content.

Stem Dry Matter Production:

In this trial conducted in Çomaklı soil, a similar ranking of wheat varieties and genotypes from small to large was observed in terms of stem dry matter production, both for -Zn and +Zn applications, as in Experiment I. It is evident that durum wheat varieties, including Kızıltan, Ç.1252, and Kunduru, produced less stem dry matter compared to other wheat varieties, while bread wheat varieties produced more, potentially placing durum wheat varieties at the bottom of the table. In Sultanönü soil, bread wheat produced more stem dry matter than durum wheat. Based on the quantities of stem dry matter produced, bread wheat was found to be less sensitive to zinc, whereas durum wheat was more sensitive. As in Experiment I, Aslım, a rye variety, produced the highest dry matter, placing itself at the top of the ranking (Table 5).

Variance analysis and Tukey's test grouping for the 15 wheat varieties grown in this soil revealed that the varieties, zinc application, and their interactions were significantly different at $P < 0.0001$. According to Tukey's test grouping, it was determined that durum wheat varieties formed a separate group from sensitive wheat varieties, along with more resistant durum wheat.

Root Dry Matter Production*:*

In terms of root dry matter production among wheat varieties under -Zn application, durum wheat varieties in Çomaklı soil produced less root dry matter, as indicated on the left side of Table 5. Bread wheat varieties, with their higher root dry matter production, were positioned on the right side of the figure. In the case of zinc application, a consistent ranking was not observed due to production differences among some varieties. Statistical analysis showed significant differences among wheat varieties, zinc application, and their interactions in root dry matter weight (Table 5).

Shoot-to-Root Ratio:

In the ranking of wheat varieties from small to large based on stem-to-root ratio, no regular order or relationship distinguishing durum and bread wheat varieties was observed (Table 5). Difficulties in root washing and cleaning may cause deviations from expected values, affecting both the stem-to-root ratio and root length results.

Root Length:

In the ranking of wheat varieties by root length, from shortest to longest, different varieties were distinguished under both zinc application conditions, such as Experiment I. However, as in the previous experiment, they are clearly distinguished from each other. In these soil conditions, durum wheat varieties were found to produce shorter root lengths compared to bread wheat varieties. Bread wheat varieties had longer root systems (Table 6). As mentioned earlier, significant challenges in distinguishing varieties arise from deficiencies in the root study method and the complexity of the subject. The examination revealed that root length is an important parameter in determining plant growth and dry matter production.

Mycorrhizal Infection:

Like Sultanönü soil, wheat plants in Çomaklı soil were not sufficiently infected with mycorrhiza, and those that were infected did not develop an effective hyphal system, as determined by microscopic examinations. There was no consistent pattern among varieties in the ranking of infection parameters ranging from small to large (Table 6).

Zinc Use Efficiency:

It is observed that zinc use efficiency does not definitively distinguish varieties from each other in terms of stem and root dry matter, root length, and mycorrhizal infection (Figure 2). Since this parameter is a qualitative evaluation of previous data, any error in the experimental design and data acquisition will be reflected here as well. Zinc efficiency refers to the correlation between values observed under zinc-free conditions and those under zinc treatments. The high correlation depends on the consistent and similar relationships among the previously determined parameters. Previously, Cakmak et al. (2001) reported that there is substantial variability in the Zn efficiency ratio, ranging from 20% to 51%. In the present experiment, efficacy ranges from 19 to 40.

Total Carbon Uptake and CO_2 Fixation

The total dry weight of different genotypes shows significant differences in C content and CO_2 fixation. In general, Zn-applied genotypes have higher carbon contents than those without Zn application. CO_2 production in –Zn-treated genotypes ranged from 1.42 g CO_2 per kg of soil to 4.38 g CO_2 per kg of soil. In +Zn-treated genotypes, CO_2 ranged from 5.54 to 11.18 g CO_2 kg soil (Table 7). Differences between +Zn and –Zn are significant, demonstrating the efficacy of Zn application in mitigating climate change driven by CO_2 concentration. Results show that the capacity of genotypes to fix carbon dioxide is enhanced by Zn application, which is essential in combating climate change.

In alignment with the research goal, the hypothesis regarding differences in root development and root length, and their impact on yield, is partially confirmed.

A highly positive correlation was identified between root dry matter weight, depending on differences between varieties in both soils. Graham and Rengel (1993) found that, in wheat genotypes experiencing Zn deficiency, some produced a significant number of fine roots (<0.3 mm) in the soil, allowing them to utilise Zn more effectively. However, in this study, fine root length was not measured, and it is crucial to determine whether genotypes produce more fine roots to utilise zinc better.

Table 4. Effects of wheat genotype, carbon content and CO_2 fixation

	g C kg soil		g CO_2 kg soil		g CO_2 kg soil
Genotypes	(-Zn)	(+Zn)	(-Zn)	(+Zn)	(+Zn-(-Zn)
ES.SBVD1-2	1,80	2,72	6,59	9,98	3,40
BDME-10	1,77	2,92	6,47	10,71	4,24
ES-91-12	1,99	2,96	7,29	10,84	3,55
DAGGER	2,35	2,71	8,62	9,92	1,30
PRESTO	2,13	2,98	7,82	10,93	3,11
ES.SBVD1-22	2,35	2,77	8,62	10,14	1,52
Ç. 1252	1,87	3,42	6,87	12,55	5,68
BEZOSTAJA	2,29	3,24	8,40	11,89	3,49
KIZILTAN	2,59	3,00	9,50	11,01	1,51
SERTAK	2,42	3,19	8,86	11,68	2,82
PARTİZANKA	2,42	3,19	8,87	11,69	2,82
ES-14	1,96	3,66	7,18	13,42	6,24
GEREK	2,47	3,26	9,06	11,95	2,89
ATAY	3,07	3,10	11,26	11,37	0,11
ES.SBVD2-23	3,15	3,12	11,56	11,45	-0,12
ES.SBVD1-21	2,83	3,48	10,38	12,78	2,40
BUL-63-68-7	2,82	3,50	10,36	12,83	2,48
ES-90-3	2,89	3,45	10,61	12,64	2,03
YAYLA	2,87	3,48	10,51	12,76	2,25
KUNDURU	2,41	3,94	8,84	14,44	5,61
ÇAKMAK	2,68	3,70	9,84	13,58	3,75
ES.SBVD2-8	2,94	3,50	10,77	12,82	2,04
ES-90-1	2,12	4,31	7,79	15,81	8,03
ASLIM	2,64	3,83	9,70	14,03	4,33
ES.SBVD2-22	2,57	3,95	9,44	14,47	5,03
KIRKPINAR	2,83	3,71	10,36	13,59	3,22
WARIGAL 5RL	2,09	4,54	7,68	16,64	8,96
NIS-22	2,93	3,70	10,76	13,57	2,81
ES-90-11	3,28	3,44	12,03	12,61	0,59
ZITAVKA	3,39	3,40	12,42	12,46	0,05
ES-90-8.1	2,38	4,56	8,73	16,73	8,00
ES-84-16	2,80	4,24	10,27	15,56	5,28
P.NISKA	3,46	3,67	12,68	13,46	0,79
BOLAL	3,56	3,61	13,05	13,24	0,19
KATE-A	3,25	4,17	11,93	15,29	3,36
ES-90-14	2,89	4,57	10,58	16,76	6,17
DAĞDAŞ	2,88	4,61	10,56	16,91	6,35
KIRAÇ	2,81	4,75	10,29	17,41	7,12
BDMM-19	3,82	3,76	14,02	13,80	-0,22
GÜN-91	5,79	4,03	21,25	14,76	-6,49

Although there is no consistent ranking of root parameters between durum and bread wheat varieties, they differ in root growth and length. The lack of a regular relationship among varieties regarding root parameters may stem from inherent errors in root-related methods. Despite these uncertainties, it is evident that plants exhibited significant differences in root development, especially in root length.

The close relationship between zinc application and root development in wheat was established in a hydroponic study (Cumbus, 1985). However, this study indicates a lack of a significant difference in zinc use efficiency among varieties. The inconsistency in the ranking of varieties may result from various parameters. As observed in both experiments under -Zn application, varieties formed distinct clusters in dry matter production, indicating differences in zinc utilisation. However, in the increased zinc (+Zn) application, plants may have compensated for the differences by absorbing the required zinc, which might explain the lack of a clear distinction (Ortas, 2024).

The findings show that improved Zn absorption and Zn-efficient genotypes can promote grain Zn biofortification and lessen "hidden hunger" in low-Zn areas. Studies of the HarvestPlus kind, for example, have demonstrated that wheat genotypes with high zinc concentrations enhance nutritional quality.

The stem-to-root ratio in the -Zn application showed that bread varieties had a higher ratio than durum varieties. This observation might be related to the varying degrees of zinc utilization by plants. In contrast, in durum varieties, root growth was higher. The stem-to-root ratio is a crucial parameter for nutrient uptake, particularly linked to the presence and effectiveness of mycorrhizae. Varieties that effectively use zinc tend to have a higher green aboveground-to-root ratio. It raises the question of which *Plant and Soil* mechanisms underlie the better utilization of Zn by these varieties.

It is known that bread wheat genotypes have a higher capacity for taking up zinc from the soil, Graham et al. (1992). Additionally, Cakmak et al. (1996) reported in their hydroponic studies that bread wheat released more phytosiderophores, leaching more zinc from the soil than durum wheat. Usually, under iron and zinc deficiency conditions (Marschner, 1995; Tinker and Gildon, 1983), Zinc, a nutrient indirectly related to mitigating climate change effects, increases plant defence systems against climate negative influences. Klofac *et al.* (2023) reported that Zn application can increase plant resistance to water stress by enhancing physiological defence mechanisms.

As seen in the literature, the lack of a clear ranking among varieties in terms of zinc use efficiency may depend on various parameters. Among these parameters, root length and mycorrhizal infection are crucial and exhibit significant differences between genotypes (Graham, 1984). However, these differences do not necessarily affect nutrient use efficiency (Tinker, 1986). This study's results align with the literature, showing that nutrient use efficiency is determined by root development and mycorrhizal infection.

The low levels of microelements in Gambia soils reported by Webb (1954) and the severe deficiencies observed in pot trials may be attributed to the effectiveness of mycorrhizal infection under field conditions. Thus, it can be speculated that mycorrhizal infection might not have been adequately established in short-term pot trials due to the use of the fungicide Benlate and the amount of phosphorus fertiliser. The amount of phosphorus fertiliser used in this trial may have played a crucial role in contributing to the inadequate mycorrhizal infection. However, in wheat trials conducted in the field section of our department, it was determined that roots were heavily infected, significantly affecting yield (Ortas et al., 1996).

As mentioned in the research findings, both experiments showed weak mycorrhizal infection in wheat roots in pot trials; it is suggested that this may be due to the fungicide Bentolit used to control fungi in greenhouse conditions. This study provides valuable insights into the challenges associated with mycorrhizal infection in short-term pot trials. The results indicate that wheat plants establish mycorrhizal infection later than many other plants, due to their characteristics. Plant root differences and dependencies on mycorrhizal infection may be important factors in determining plant genotypes' resistance to nutrient deficiency, drought, and other stressors. Singh et al.'s (2012) results indicated that durum wheat genotypes should be chosen for their AMF compatibility rather than their mycorrhizal dependence. Estaún et al. (2010) indicated that to develop a comprehensive breeding strategy for crop cultivars that fully utilise the arbuscular mycorrhizal symbiosis, new breeding approaches should consider the metabolic and genetic findings of plant hosts. Overall, this study contributes to understanding the complex relationships among wheat varieties, soil conditions, and nutrient utilisation, particularly regarding zinc. The results emphasized the importance of considering multiple factors, including root parameters, mycorrhizal infection, and stem-to-root ratio, in assessing nutrient use efficiency in wheat varieties.

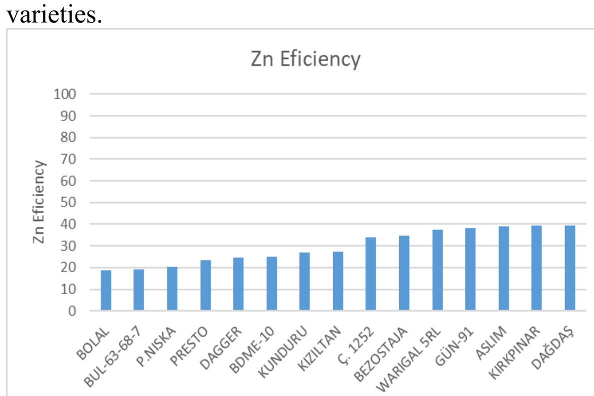

Figure 2. Zinc use efficiency (%) of fifteen genotypes grown on Çomaklı soil

Table 5. effects of Zn application on 15 wheat varieties in Çomaklı soil

Wheat Genotype	Shoot dry weight(g/10 plants)				Root dry weight (g/10 plants)				Shoot/root	
	-Zn		+Zn		-Zn		+Zn		Zn/+Zn	
KIZILTAN	0,92	±0,12	3,22	±0,24	0,34	±0,07	1,34	±0,17	2,71	2,01
BUL-63-68-7	0,94	±0,17	4,87	±0,34	0,30	±0,07	1,63	±0,56	3,16	2,99
Ç. 1252	1,02	±0,25	4,06	±0,18	0,47	±0,14	1,39	±0,17	2,34	2,81
KUNDURU	1,03	±0,27	4,01	±0,77	0,42	±0,02	1,10	±0,34	2,44	3,64
BDME-10	1,06	±0,17	5,24	±0,46	0,74	±0,29	2,55	±0,49	1,19	2,05
PRESTO	1,06	±0,05	5,77	±0,63	0,87	±0,07	2,39	±0,17	1,22	2,42
BOLAL	1,11	±0,15	5,93	±0,65	0,87	±0,05	2,16	±0,20	2,32	2,74
P.NISKA	1,12	±0,14	5,80	±0,32	0,46	±0,09	1,97	±0,21	2,42	2,95
DAGGER	1,14	±0,09	5,31	±0,22	0,51	±0,07	1,37	±0,09	2,25	3,87
GÜN-91	1,52	±0,21	4,89	±0,10	0,97	±0,06	1,64	±0,09	1,57	2,98
KIRKPINAR	1,59	±0,37	4,88	±0,52	0,84	±0,12	1,68	±0,01	1,89	3,74
DAĞDAŞ	1,62	±0,09	5,34	±0,35	1,12	±0,09	2,10	±0,09	1,45	2,31
BEZOSTAJA	1,75	±0,12	5,63	±0,19	0,95	±0,09	2,17	±0,07	1,85	2,60
WARIGAL 5RL	2,01	±0,19	5,94	±0,75	0,82	±0,07	1,59	±0,10	2,46	3,73
ASLIM	2,21	±0,38	7,30	±0,99	1,60	±0,29	2,43	±0,36	1,38	3,00

Table 6. Effects of wheat genotype on root length and mycorrhizal colonisation

	Root length				Mycorrhizal infection (%)			
Wheat genotype	-Zn		+Zn		-Zn		+Zn	
KIZILTAN	36,90	±11,30	65,76	±15,30	18	±3	41	±3
BUL-63-68-7	21,61	±8,46	83,89	±20,69	28	±2	33	±2
Ç. 1252	47,52	±16,12	77,83	±24,01	36	±3	38	±3
KUNDURU	15,03	±0,60	32,43	±1,30	23	±3	24	±4
BDME-10	84,20	±10,20	98,30	±19,50	18	±2	38	±3
PRESTO	45,75	±15,10	70,69	±13,87	26	±2	28	±4
BOLAL	35,34	±7,46	58,66	±6,92	22	±2	41	±4
P.NISKA	35,02	±12,58	90,46	±25,16	29	±2	31	±2
DAGGER	44,39	±8,45	80,64	±19,46	31	±2	33	±4
GÜN-91	40,29	±18,12	71,78	±23,17	27	±3	31	±6
KIRKPINAR	40,18	±17,41	53,59	±9,79	30	±3	31	±5
DAĞDAŞ	50,97	±7,49	87,80	±22,21	31	±3	40	±5
BEZOSTAJA	50,80	±5,66	98,87	±20,27	30	±3	33	±4
WARIGAL 5RL	26,95	±8,23	50,11	±21,68	19	±3	33	±5
ASLIM	63,29	±15,41	76,35	±24,32	29	±3	33	±4

Table 7. Effects of wheat genotype carbon content, and CO_2 fixation

Wheat genotype	g C kg soil		g CO_2 kg soil		g CO_2 kg soil
	(-Zn)	(+Zn)	(-Zn)	(+Zn)	(+Zn-(-Zn)
BUL-63-68-7	0,39	2,04	1,42	7,47	6,05
KIZILTAN	0,41	1,51	1,51	5,54	4,03
KUNDURU	0,43	1,60	1,58	5,88	4,30
BOLAL	0,48	2,54	1,74	9,30	7,55
P.NISKA	0,50	2,43	1,82	8,92	7,10
DAGGER	0,52	2,09	1,89	7,67	5,78
PRESTO	0,60	2,56	2,21	9,38	7,16
BDME-10	0,61	2,44	2,24	8,95	6,71
Ç. 1252	0,69	2,02	2,51	7,40	4,89
KIRKPINAR	0,76	1,94	2,80	7,11	4,31
GÜN-91	0,78	2,05	2,86	7,51	4,65
BEZOSTAJA	0,85	2,45	3,10	8,97	5,86
DAĞDAŞ	0,86	2,17	3,14	7,96	4,82
WARIGAL 5RL	0,88	2,36	3,24	8,65	5,41
ASLIM	1,19	3,05	4,38	11,18	6,80

CONCLUSION

Under Zn-deficient conditions, the root dry matter and root lengths produced by durum and bread varieties differed more significantly than those produced under +Zn conditions. It was found that different wheat varieties did not differ in mycorrhizal infection under either soil condition, with or without zinc application. Bread wheats exhibited greater tolerance to Zn Deficiency than durum for shoot biomass, root vigour, and root length, with resistant candidates (e.g., Kırkpınar, Bezostaja) consistently outperforming sensitive durum (e.g., Kızıltan, Ç.1252, Kunduru). Aslım (rye) set the upper bound for biomass under both Zn regimes. AM symbiosis effects were variable under pot conditions.

In addition, wheat genotypes are significantly sequestering high levels of CO2, which serves as an essential mitigation strategy. Given the consistent rise in C content and CO_2 fixation with +Zn, Zn nutrition should be integrated into nutrient-climate strategies where soil Zn is limiting; +Zn more than doubled shoot biomass on average and enhanced estimated CO_2 fixation—implicating Zn management as a co-benefit strategy for both yield and carbon sequestration.

CONFLICT OF INTEREST

The author here declares there is no conflict of interest in the publication of this article.

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