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Interactions between Zn, Fe, Cu and Mn in Various Organs of Bread Wheat at Deficiency and Adequate of Absorbable Zinc

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Abstract

Deficiency or restriction of Zn absorption in soils is one of the most common micronutrients deficient in cereal plants. To investigate critical micronutrient interaction in zinc deficiency and zinc sufficient in soil, a factorial experiment based on completely randomized design (CRD) with three replications was conducted in 2023. Six wheat cultivars with different Zn efficiency were used. The cultivars were grown under Zn deficiency and adequate conditions. Results showed that in Zn deficiency conditions, with increasing Zn concentration in the roots, Fe concentrations were increased too, while the Cu and Mn concentrations decreased. In the same condition and with increasing Zn concentration in shoots, the concentrations of Fe and Mn decreased, while Cu were increased. However, by increasing Zn concentration, Fe, Cu, and Mn concentrations were increased in Zn deficiency condition in grains, as well as Zn sufficient conditions. RST (root to shoot micronutrient translocation) comparison of cultivars showed that in lack of Zn, the ability of translocation of Zn, Fe, and Mn in Zn-inefficient cultivar from root to shoot was higher than inefficient cultivar. In the same conditions, the capability of Zn-inefficient cultivar in Cu translocation from root to shoot was lower than other cultivars. In general, it seems that in Zn deficiency conditions, there are antagonistic effects among Zn, Cu and Mn and synergistic effects between Zn and Fe in the root. Also, in Zn sufficient conditions, there were synergistic effects among all studies micronutrients which include Zn, Fe, Cu, and Mn.

Keywords

Interaction, Micronutrient, Translocation Ratio, Zn Deficiency, Zn-Efficient

1. Introduction

Micronutrients are crucial in small amounts for plants (>100 mg·kg^{-1} dry weight)

[1], however these elements are essential for their growth and developments [2]. They contribute into almost all metabolic and cellular functions such as photosynthesis, metabolism, cell protection, gene regulation, hormone perception, signal transduction, and reproduction [3] and have critical roles in various cellular and molecular process in plants such as chlorophyll synthesis, photosynthesis (Zn, Cu, Fe, and Mn), respiration (Cu and Fe), stabilization of DNA and gene expression (Zn) [4].

This volume of role in the current vital cellular functions has caused the deficiency of these nutrients, not only to cause a quantitative decline in plants, but also to reduce the quality of products consumed by humans and animals. More than 50% of the overall world's population is affected by micronutrient malnutrition. This fact has caused that micronutrient deficiency in food sources has emerged as one of the serious global challenges for human life [5].

For any reason, if micro element's absorption or their balance in the plant was disturbed, the current plant physiological process will be affected and finally quantitative and qualitative yield will be reduced. The abundance of elements affects soil biology, while deficiency of elements harms plant growth and development [6] [7]. Therefore, it seems that plants need the optimal level and amounts of elements for their natural growth and function [7]. It is believed that cells have proper ionic homeostasis, which is necessary to absorb, use and store elements in plants in a balanced way [8]. Balance in the absorption of microelements is one of the most important factors in the natural growth of plants and increasing crop yield [9].

Whole soil zinc (Zn) availability is influenced by various factors involved in soil Zn accessibility for plants including the physicochemical properties of the soil, the activity of plant roots, the microflora present in the rhizosphere, along with other non-edaphic factors, biological factors such as plant species and non-biological such as climate, total absorbable Zn concentration, soil pH, temperature, calcium carbonate, soil organic materials, soil texture, microbial activity, salinity, flooding, and interaction of Zn with other elements such as Fe, Cu, Mn, P, Mn [9]. Zinc (Zn) deficiency is one of the most widespread nutritional limitations in plant products, especially cereals. According to the World Food Organization (FAO) reports, about half of the farming soils have Zn leakage [9]. Low soil Zn availability significantly affects the yield and nutritional quality of cereals, especially bread wheat [10]. When interactions occur between elements, changes begin at the intracellular level, which may eventually be revealed by changes in transpiration, cell division and development, photosynthesis, and the usage or transport of carbohydrates and organic acids. The outcome of interactions determines the final quantitative and qualitative crop yield. Interactions between nutrients in agricultural products occur when the value of one element influences absorption or usage of other elements by the plants. Nutrients can increase (Synergic), or decrease (Antagonist) absorption, or do not affect each other. Interaction of elements can happen at the root level or within the plant and be divided into two general groups. The first interaction between the ions because of their ability to create chemical bonds between each other occurs. Interactions in this type are due to the formation of sediments or complexes. The second type of interaction is between ions that have sufficiently similar chemical properties to compete for uptake, transport, and mobility in root or plant tissue levels [6]. This type of interaction between ions of Zn, Fe, Cu, Mn, Ca, P, and Na is very common. The interactions between ions of the cation-cation, and anion-anion are mainly present at the cell membrane surface, and in terms of the nature of nature, there is evidence that they are important first. Erenoglu *et al.* (2002) reported that the cation content of plant material depends on the ability of the cation to access the plant itself and the presence or absence of other cations in the plant growth medium. The aim of this study was to emphasize the importance of interactions between trace elements zinc, iron, copper and manganese in zinc deficiency conditions and compare it with adequate zinc conditions in bread wheat. It is assumed that the information obtained from this study improves the understanding of how to create a balance in low food elements for optimal growth.

2. Materials and Methods

2.1. Experimental Details

The experiment was carried out in Faculty of Agriculture research greenhouse of Agricultural and Natural Resources Research Center, Urmia, West Azerbaijan, Iran during spring and summer seasons of 2023. After preparing from the riverbed of "Khan Arkhi" river (Northwest of Urmia University, Urmia, Iran), the sandy soil was passed through a 4 mm sieve. The sand was washed with tap water 5 times to remove organic matter, minerals, and soluble salt, and rinsed with deionized water. The sand was then allowed to dry thoroughly. The Physical and chemical properties of the sandy soil are given in **Table 1**. The air-dried sand was packed into clear plastic bags in 1 kg portions. According to Genc *et al.* (2007), the basal nutrients were added to the soil and mixed. In addition to the basal nutrients, Zn (10 mg·kg^{-1}) was added to half of the pots in the form of $ZnSO_4 \cdot 7H_2O$ for the adequate Zn treatment.

Table 1. Physical and chemical properties of the sandy soil used in the current study.

Sand	Silt	Clay	Zn*	Fe*	Mn*	Cu*	K	P	OM	CaCo^3	pH	Ec
	%				(mg·kg^{-1})					%		(mmoh·Cm^{-1})
86	11	3	0.23	4.87	0.87	0.07	9.2	1.8	0.09	9	8.0	1.21

*DTPA-extractable.

2.2. Plant Material and Growth Conditions

According to the available reports, Azadi and Bayat cultivars (Zn-efficient), Niknejhad and Marvdasht cultivars (intermediate), Karaj-1, and Hirmand cultivars (Zn-inefficient cultivars) were selected [11]. The experiment was established in a greenhouse under natural light with a mean photoperiod of 14 - 10 h day/night, at 28˚C and 20˚C average temperatures during the day and night, respectively. The bread wheat seeds were surface sterilized with 70% ethanol for 3 min, 1% sodium hypochlorite for 5 min, and then rinsed with double deionized water. Polyethylene-lined cylindrical PVC pots (15 cm diameter × 35 cm depth) were filled with approximately 5.5 kg of the soil. Ten seeds were planted in each pot and after 10 days, seedlings were thinned to seven following emergencies. During the growth period, plants were weighted and watered daily with double deionized water to maintain FC and to prevent nitrogen deficiency, every 14 days ammonium nitrate was given to the plants with irrigation water.

2.3. Experimental Treatments and Design

The experimental treatments included six bread wheat cultivars with various Zn use efficiency pictorially combined with two Zn levels (without Zn application and application of 10 mg of Zn per kg of soil), and three organs (root, shoot, and grain). The treatments were arranged in a completely randomized design (CRD) with three replications. Root and shoot samples were harvested at 30% of the heading and grains at maturity. Roots were gently rinsed in deionized water to remove sand particles and were transferred to the soil science laboratory to measure the micronutrient concentration. All samples (roots, shoots, and grains) oven-dried at 68˚C for 48 h. Micronutrient quantification were performed using the dry digestion method [12] by atomic absorption UV Spectrophotometer Model "PG instruments-T80+, United Kingdom".

2.4. Calculations and Statistical Analysis

The Zn use efficiency index (ZUE) was performed on all cultivars [12]. Pearson correlation coefficients were calculated for the micronutrients of roots, shoots, and grains by using the statistical software SAS (version 9.2). Root to shoot micronutrient translocation (RST) and micronutrient translocation ratio (MTR) were measured [12].

$$\text{ZUE (\%)} = (Y_{-\text{Zn}} / Y_{+\text{Zn}}) * 100 \qquad (1)$$

ZUE: Zn use efficiency index, $Y_{-\text{Zn}}$: shoot dry matter at Zn deficiency, $Y_{+\text{Zn}}$: shoot dry matter at Zn adequate.

$$\text{RST (\%)} = (\text{SMC}/\text{RMC}) * 100 \qquad (2)$$

RST: root to shoot micronutrient translocation, SMC: shoot micronutrient concentration, RMC: root micronutrient concentration.

$$\text{MTR (\%)} = (\text{RST}_{-\text{Zn}}/\text{RST}_{+\text{Zn}}) *100 \qquad (3)$$

MTR: micronutrient translocation ratio, $\text{RST}_{-\text{Zn}}$: root to shoot translocation at Zn deficiency, $\text{RST}_{+\text{Zn}}$: root to shoot translocation at Zn adequate.

3. Results and Discussion

3.1. Micronutrient Correlation Analysis

The results of correlation analysis showed that in both conditions of scarcity and deficiency of Zn, the concentration of this element in shoot and seed was increased by increasing the absorption and accumulation of Zn in the root (**Table 2**). Likewise found that in Zn deficiency conditions in the roots, there is a positive and significant correlation (r = 0.98**) between Zn and Fe concentration. The cause of the positive correlation between Zn and Fe concentrations in Zn deficiency conditions can be attributed to the increased phytosiderophore release by the root in the Zn or Fe deficiency conditions (Strategy II) [13] or the excitation of genes involved in production of metal transporter proteins such as *ZIP* [6], Nicotianamine and *YSL* genes [14] which are involved in the absorption and transfer of both metals.

Table 2. Correlation coefficients among Zn, Fe, Cu and Mn concentrations of root, shoot and grain in bread wheat under Zn deficiency and Zn adequate conditions.

		RZC	SZC	GZC	RFC	SFC	GFC	RCC	SCC	GCC	RMC	SMC
SZC	−Zn	0.93**	1									
	+Zn	0.99**	1									
GZC	−Zn	0.91*	0.93**	1								
	+Zn	0.83*	0.84*	1								
RFC	−Zn	0.98**	0.93**	0.90*	1							
	+Zn	−0.66	−0.67	−0.85*	1							
SFC	−Zn	−0.76	−0.60	−0.52	−0.67	1						
	+Zn	−0.60	−0.58	−0.87*	0.75	1						
GFC	−Zn	0.97**	0.94**	0.87*	0.99**	−0.64	1					
	+Zn	0.55	0.59	0.90*	−0.71	−0.84*	1					
RCC	−Zn	−0.95**	−0.95**	−0.90*	−0.93**	0.79	−0.90*	1				
	+Zn	0.85*	0.86*	0.99**	−0.78	−0.83*	0.88*	1				
SCC	−Zn	0.93**	0.86*	0.74	0.92**	−0.68	0.96**	−0.83*	1			
	+Zn	−0.72	−0.74	−0.97**	0.92**	0.86*	−0.91*	−0.94**	1			
GCC	−Zn	0.91*	0.83*	0.81*	0.83*	−0.80	0.85*	−0.85*	0.88*	1		
	+Zn	0.82*	0.81*	0.93**	−0.93**	−0.77	0.71	0.90*	−0.93**	1		
RMC	−Zn	−0.97**	−0.93**	−0.94**	−0.97**	0.70	−0.94**	0.98**	−0.84*	−0.81*	1	
	+Zn	0.83*	0.86*	0.98**	−0.91*	−0.78	0.85*	0.95**	−0.98**	0.95**	1	
SMC	−Zn	−0.94**	−0.99**	−0.91*	−0.95**	0.59	−0.97**	0.93**	−0.91*	−0.84*	0.94**	1
	+Zn	0.84*	0.84*	0.49	−0.27	−0.14	0.17	0.57	−0.34	0.54	0.51	1
GMC	−Zn	0.94**	0.90*	0.94**	0.95**	−0.67	0.90*	−0.95**	0.77	0.76	−0.99*	−0.88*
	+Zn	0.84*	0.87*	0.99**	−0.83*	−0.82*	0.91*	0.97**	−0.95**	0.88*	0.98**	0.50

* and **: non-significant and significant at the 5% and 1% probability level, respectively; RZC: root Zn concentration, SZC: shoot Zn concentration, GZC: grain Zn concentration, RFC: root Fe concentration, SFC: shoot Fe concentration, GFC: grain Fe concentration, RCC: root Cu concentration, SCC: shoot Cu concentration, GCC: grain Cu concentration, RMC: root Mn concentration, SMC: shoot Mn concentration, GMC: grain Mn concentration, −Zn: Zn deficiency, +Zn: Zn adequate.

Transition of Zn from the endosperm cavity into the modified aleurone, aleurone and then to the endosperm is mainly regulated by ZIP and YSL transporters [15].

Various families of transporters and genes are involved in the regulation of zinc uptake in wheat roots. The ZIP family plays a crucial role in controlling zinc absorption. In particular, the transporters TaZIP3 and TaZIP7 from the ZIP family show increased expression in the roots of wheat plants that are deficient in zinc, which enhances both the uptake of zinc and its transport from the roots to the shoots [15]-[17].

Certain wheat cultivars generate mucilage acid (MA) in response to low zinc availability, which can help in enhancing zinc uptake [18] [19].

Members of the YSL transporter family, particularly TaYS1A, TaYS1B, TaYSL3, TaYSL5, and TaYSL6, show high expression levels in wheat roots when iron is limited [20]. The YSL transporter family are involved in the absorption of zinc from the soil in the form of a zinc-mucilage acid complex because of iron uptake. Additionally, it is possible that the zinc-mucilage acid complex dissociates near the root surface, leading to an increase in free Zn^{2+} concentration in the diffusion zone, which would enhance the uptake of Zn^{2+} [15]. Under suitable Zn conditions, a high non-significant ($r= -0.66$) negative correlation was observed between Zn and Fe concentration in roots. It seems that under sufficient Zn conditions, there are antagonistic properties in the roots between the two elements, and as a result, bread wheat under sufficient Zn conditions is preferable to the absorption of Fe insufficient conditions. The antagonistic effect between Zn and other cationic trace elements such as Fe, Cu, and Mn has been reported in various studies [2]. Studies conducted that when two elements (Fe and Zn) are sufficiently available in the soil, the Zn absorption will interfere with the absorption and transfer of Fe. While the Fe uptake only occurs when the concentration on the environment is too much for the plant [14]. Various mechanisms have been proposed for the antagonistic effect of Zn and Fe. In this regard, it has been suggested that the two Zn^{2+} and Fe^{2+} ions can compete during the absorption by the root over occupation centers, and on the other hand, Zn can interfere with the clotting process during uptake and transfer of Fe [17]. On the other hand, it seems these two elements can compete with each other in draining to xylem [14]. Finally, evidence suggests that some proteins encoded by ZIP genes, which are the main transporters in the transport of Zn and Fe, prefer Zn to Fe when sufficient amounts of two elements are presented [18]. Cheema *et al.* (2018) believes that one of the reasons for preferring the uptake and transfer of Zn to Fe by wheat roots in conditions of sufficient Zn and Fe elements in the soil is the use of type II strategy by this plant to absorb Fe. Wheat root releases trivalent Fe with strong bonds by secreting phytosiderophores in the rhizosphere. A large portion of the Fe absorbed by the plant is transferred to this method in the xylem. Because the transfer of Zn is in free ions and Fe is in a relatively large combination form, assumed that the transfer of Zn overcomes Fe in the competition for uptake by plants [5]. Ghasemi and

Ronaghi (2008) reported that under sufficient Zn and Fe conditions in the environment, there is an antagonistic property between the two elements, however, the transfer of zinc was more affected by the uptake of iron by the roots [19]. Reduction of Fe concentrations in rice roots and shoots with increasing Zn has been reported by Hänsch and Mendel (2009) [20]. Correlation analysis shows that there is a significant negative correlation between Zn and Cu (−0.95**) and Mn (−0.97**) in Zn deficiency conditions at the root. Zn and Cu affect each other in several ways and prevent each other from being absorbed. Cu competitively inhibits the uptake of Zn from the soil and increasing soil Cu affects the redistribution of Zn within the plant [21]. Kumar *et al.* (2009) reported that in Zn-deficient wheat, there is a very strong antagonism between Zn and Cu. Inhibition of competitive absorption of Cu^{2+} ions on Zn^{2+} uptake has also been demonstrated in short-term studies [22]. On the other hand, it is believed that in root uptake sites, Zn^{2+} activity is much higher than Cu^{2+}, which makes it an effective competitor for Cu uptake and ultimately limits Cu absorption [23]. High concentrations of Cu compared to Zn in soil due to competition for similar absorption sites in plant roots [14] or competition of these two elements to occupy common sites in identical transporters [5] can reduce the availability of Zn (and versa) for the plant. Studies have also shown that proteins encoded by Zn transporters encoding genes, specifically ZIP transporters, are involved in the transport of Cu and Mn [18], and in the case of Zn deficiency Cu and Mn compete with Zn for transmission by these transporters. Insufficient Zn conditions, in contrast to Zn deficiency conditions, a positive and significant correlation was observed in the roots between Zn and Cu (0.85*) and Mn concentration (0.83*). It seems that when the soil has enough Zn, Cu, and Mn, these elements not only have no antagonistic effect on the uptake but probably increase the absorption, transport, and storage of each other in the roots by a synergistic effect. According to the results of correlation analysis, in the case of Zn deficiency in shoots, a negative but not significant correlation is observed between Zn and Fe concentration (−0.60). In some conditions, there is a positive and a significant negative correlation between Zn and Cu (0.86*) and Mn (−0.99**) concentrations, respectively. It seems that when the amount of Zn in the soil is less than the plant needs, there is no competition between Zn and shoot transfer. In contrast to Cu, in the case of Zn deficiency, the transfer and storage of Mn significantly interfere with the transfer and storage of Zn. In shoots, under sufficient Zn conditions, there is a negative and non-significant correlation between Zn and Fe (r= −0.58) and Cu (r= −0.74) and Mn concentration (r= 0.84*). The antagonistic effects of Zn and Fe were sufficiently discussed above. Kumar *et al.* (2009) showed that the use of sufficient Cu has a negative effect on the uptake and storage of Zn in wheat shoots. Several studies reported a positive and significant correlation between Zn and Mn concentrations under adequate Zn conditions in wheat shoots [24]. In wheat in both Zn sufficiency and Zn deficiency conditions between Zn and Fe concentrations (0.87 and 0.90*, respectively), Cu (0.81 and 93**, respectively), and Mn (0.94 and 0.99** respectively) showed a positive and significant correlation. It seems that at the end of the growth period of wheat and when the grain is full, wheat uses mechanisms that, regardless of the environment, can transfer the maximum required microelements to the grain. Therefore, it should use any factor that can be effective in increasing the transfer of elements and their storage in the grain and prevent the factors that are involved in the metal competition and interfere with the transfer of elements to the grain. Karen *et al.* (2005) in the study of concentration of microelements in the application of different amounts of Zn fertilizer noticed that with increasing Zn in the soil more than normal, the amount of Cu and Mn in bean seeds also increased significantly [3]. In this regard, Kumar *et al.* (2009) reported that the concentration of Zn in wheat grain showed no significant change with increase of Cu application and remained constant. It is noted that in deficiency and also sufficient conditions of Zn, between concentrations of Zn in roots and Zn ($r = 0.91^*$ and $r = 0.83^*$, respectively), Fe ($r = 0.97^{**}$ and $r = 0.55$, respectively), Cu ($r = 0.91^{**}$ and $r = 0.82^*$) and Mn ($r = 0.94^{**}$ and $r = 0.84^*$ respectively) in grain (except for Fe under sufficient Zn conditions) there was a positive and significant correlation [24]. A previous study of genes involved in Zn absorption (*ZIP* genes) showed that most of these genes become active during spike growth period, so it seems at the end of the wheat-growing season (spike stage) and during grain formation, in order for the grain to be enriched with the required metals, the activity of these genes in the root increases and they increase the absorption and transfer of metals from the root to the shoot and finally to seed [25].

3.2. Root to Shoot Translocation of Micronutrient (RST)

First, for all the studied cultivars, ZUE was calculated. Among the varieties, two varieties Azadi with ZUE = 0.96 and Hirmand with ZUE = 0.81 respectively with the highest and lowest ZUE to study and compare the transfer capability of microelements, were selected.

To compare the ability to transfer microelements from root to shoot of cultivars with different ZUE, for each cultivar, in both Zn sufficiency and Zn deficiency conditions, RST and MTR were calculated (**Table 3**). The results showed that in Zn deficiency conditions, the relative transfer of Zn, Fe and Mn elements from root to shoot and also their transfer ratio in Azadi is less than Hirmand.

Table 3. Root to shoot translocation and Shoot translocation ratio of Zn, Fe, Cu and Mn in Azadi (Zn-efficient) and Hirmand (Zn-inefficient) cultivars under Zn deficiency and Zn adequate conditions.

	Zn RST (%)		MTR (%)	Fe RST (%)		MTR (%)	Cu RST (%)		MTR (%)	Mn RST (%)		MTR (%)
	−Zn	+Zn		−Zn	+Zn		−Zn	+Zn		−Zn	+Zn	
Azadi	70.03	64.08	109.28	24.50	79.11	22.42	35.48	53.40	66.44	61.72	56.11	110.00
Hirmand	81.60	59.73	136.61	45.61	87.46	52.15	23.32	27.65	84.34	67.78	49.70	136.38

RST: root to shoot translocation, −Zn: Zn deficiency, +Zn: Zn adequate, MTR: micronutrient translocation ratio.

In the case of Zn deficiency, Zn-efficient compared to Zn-inefficient cultivars, transfer a few absorbed microelements, especially Zn, and spend a significant amount of Zn on metabolism and dry matter production. Instead, inefficient Zn cultivars prefer to transfer more microelements, especially absorbed Zn to shoots or may not be able to use them in current metabolism and biomass production. It is referred to as high ability in "utilization of available Zn" or "Utilization efficiency", which is one of the main indicators of separation of Zn-efficient cultivars from Zn-inefficient cultivars [11]. Generally, efficiency refers to the amount of dry matter (biomass) produced by the plant under Zn deficiency stress relative to biomass produced under the presence of Zn [26]. Graham *et al.* (1992) believed that in order to for a plant to be Zn-efficient, it must not only be able to absorb Zn from Zn-deficient soils, but also must be able to produce dry matter and high yields under the same conditions [2]. In the present study, it was observed that in Zn deficiency conditions, the concentration of Zn stored in the root of Azadi cultivar (44.75 mg·kg^{-1}) was significantly higher than the Hirmand cultivar (30.58 mg·kg^{-1}) (results not shown). Therefore, it seems that Azadi cultivar as a Zn-efficient cultivar (ZUE = 0.96) has more ability to absorb Zn by the root than Hirmand as Zn-inefficient cultivar (ZUE = 0.81) and in addition, is able to spend more of the absorbed Zn to produce and increase dry matter in the shoot which is consistent with the results of Haslett *et al.* (2001). According to Genc *et al.* (2006), several mechanisms at the molecular, physiological, and structural levels are involved in the ZUE, however, the absorption is the main mechanism in the ZUE that improves with increasing physiological efficiency [27]. Studies show that Zn is constantly being transferred into the system and between the organs of wheat [7] [24]. On the other hand, under Zn deficiency conditions, remobilization of Zn from old organs (Sensing) to use in the growth and biomass, plays a role in wheat genotypes Zn uses efficiency index [11]. Hajiboland *et al.* (2001) reported that tolerance to Zn deficiency by a Zn-efficient rice genotype, besides the ability to absorb the Zn by the root, depends on its ability to remobilize Zn from old leaves to growing and emerging leaves [22]. However, studies conducted by Erenoglu *et al.* (2002) on wheat for two consecutive years did not confirm this finding. It has been reported that in comparison with Zn-inefficient chickpea genotypes (Tyson and Dooen) and Zn-efficient genotypes (CTS-11308 and T-1587), more than 70% of root-absorbed Zn was transferred to shoots [14] which has no similar result to the results of our study. However, no enough information has been published on the transfer of Zn and other microelements from roots to shoots or from shoots to other plant organs, especially in cases of Zn deficiency. In this regard, Ajeesh Krishna *et al.* (2017) showed that in Zn deficiency conditions, the relative transfer of Zn to shoots in 12-day treatments in the rye (Aslim cultivar) was higher than ZUE bread wheat (Dagdas-94 cultivar), and it's more than the Zn-inefficient cultivar (BDME-10 cultivar) and finally, all were more than durum wheat (cultivar Kunduru-1149) [28] [29]. Subsequently, they believe that Zn-efficient cultivars, in addition to having root zinc concentration in zinc deficiency conditions, also have more zinc transfer capacity to shoots. Considering that the results presented by these researchers were obtained in nutrient solution conditions and in a very limited time (12 days), but the present study was conducted in conditions relatively similar to the natural growth environment of bread wheat and sampling at a time when bread wheat has sufficient time for its growth period, the results presented in the present study seem to be closer to reality and therefore the relative transfer of zinc to shoots in Zn deficiency conditions can't be used as a valid indicator for the efficiency approach which was used in bread wheat. Under sufficient zinc conditions, the transfer to shoots of Zn elements (64.08%), Cu (53.40%), and Mn (56.11%) in Azadi was significantly higher than Hirmand (59.73%, 27.65%, and 49.70%, respectively). The present study indicated that in comparison with the Hirmand Zn-inefficient cultivar, the Azadi Zn-efficient cultivar had more dry weight and shoot fresh weight in both Zn and Zn deficiency conditions (results are not shown) [30]. Likewise under adequate zinc conditions, zinc-efficient cultivars not only have a great ability to absorb and use Zn in the soil, but also their ability to transfer absorbed Zn, Cu and Mn to shoots is more than Zn-inefficient cultivars. An important point in the results of the study of Zn transfer power to shoots is that, the value of this index in both cultivars was higher in Zn deficiency than Zn sufficient conditions. This could mean that in conditions of Zn deficiency, bread wheat cultivars with different ZUE use less amount of absorbed Zn to produce root dry matter and transfer most of the absorbed Zn to shoots. The reason for this behavior may be described by the fact that bread wheat in order to produce the best seed, with the most ideal vigor (which will guarantee the survival of the plant generation in future generations), needs to produce as many seeds as possible that have the most essential nutrients stored, therefore it is necessary to avoid the use of elements in the production of biomass as much as possible in the deficiency of elements, and conduct the most of these elements to the grain [31]. To study the dynamics of elements and comparison between cultivars, by dividing the transferability of elements in zinc deficiency conditions by the transferability of the same element insufficient zinc conditions, the element transfer ratio index was calculated [2]. The results showed that the dynamics of all studied elements in Azadi cultivar were significantly lower than Hirmand cultivar. From this observation, it can be concluded that the mechanism responsible for the metabolism of Zn-efficient cultivars consumes the most of these essential elements and prevents their transfer between root and shoot. In contrast to these cultivars, Zn-inefficient cultivars are not able to use these elements and the most of these elements are going back and forth between the roots and shoots. Comparison of the transfer ratio of the four studied microelements shows that Zn and Mn together have the highest dynamics between the roots and shoots. In this regard, the two elements Cu and Fe are in the next ranks, respectively.

4. Conclusion and Discussion

As expected, the correlation between Zn concentration and the concentration of the studied elements under adequate and Zn deficiency was different in both root and shoot organs, but not in the seeds. In Zn deficiency conditions, with increasing of Zn concentration in roots, Fe concentration increased, but Cu and Mn concentrations decreased. However, in the same conditions in shoots, with increasing Zn concentration, Fe and Mn concentrations decreased and Cu concentration increased. While under sufficient Zn conditions, the concentrations of Cu and Mn in the roots, as well as Mn content in shoot, increased due to enhancement of the Zn. Although, in grain under both adequate Zn and Zn deficiency conditions, increasing the concentration of Zn had no negative effect on the concentration of other elements, so that with increasing the concentration of Zn, the concentration of Fe, Cu, and Mn in the grain also increased. Finally, in both conditions, adequate Zn and Zn deficiency, the concentration of Zn, Fe, Cu, and Mn increased in the grain by increasing the concentration of Zn in the roots. In Zn deficiency, the ability of Zn-inefficient cultivar to transfer absorbed Zn, Fe, and Mn by roots to shoots was higher than Zn-efficient cultivar. Under the same conditions, the ability of the Zn-inefficient cultivar to transfer Cu as a low consumption element to shoots was less than the Zn-inefficient cultivar. The ability of Zn and Mn to transfer from the root to the shoot was significantly higher than Fe and Cu. The results of the present study were consistent with a number of studies and also contradicted some. Due to the fact that different studies have been performed under their own environmental conditions, as well as the forms and ions of the Zn element used in field studies, foliar spraying, and the solutions used in laboratory studies, these results are different. And sometimes the paradox is not unexpected. In the present study, we tried to maximize the simulation of natural plant growth conditions (except for greenhouse environment) including culture medium (soil) as well as the forms of applied Zn (Zn sulfate). Therefore, it seems that the results obtained in the present study are more valid and more generalizable than many similar experiments mentioned in the results and discussion section. In general, it can be said that in Zn deficiency conditions, in the root, there is an antagonistic effect between Zn, Cu and Mn, also a synergistic effect between Zn and Fe, and in sufficient Zn conditions, there is a synergistic effect between Zn and Cu and Mn elements. But at the same time, in both deficient and sufficient Zn conditions in grain, which is the most important economic organ of bread wheat, there is a synergistic effect between all four important low-consumption elements (microelement) of Zn, Fe, Cu, and Mn.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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