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The Effect of Micronutrients in Ensuring Efficient Use of Macronutrients

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Abstract: Micronutrient deficiency is widespread in many Asian countries due to the calcareous nature of soils, high pH, low organic matter, salt stress, continuous drought, high bicarbonate content in irrigation water, and imbalanced application of fertilizers. Some of the adverse effects of micronutrient deficiency-induced stress in plants include low crop yield and quality, imperfect plant morphological structure (such as fewer xylem vessels of small size), widespread infestation of various diseases and pests, low activation of phytosiderophores, and lower fertilizer use efficiency. The absence of micronutrient fertilizers results in inadequate absorption of trace elements by plants, which causes substantial yield losses in different crops and forages, and eventually results in poor health for domestic animals and humans. Calcareous soil research results of the last decade show that at the present time, among micronutrients, Zn deficiency is the most detrimental to effective crop yield. Other important micronutrients that increase crop yield (most to least effect) are Fe, B, Mn, Cu, and Mo. In the case of calcareous soils, the conventional notion that micronutrients increase crop yield by 15%-30% is an underestimated range. In fact, in some cases, especially with inefficient cultivars such as durum wheat (*Triticum durum* L.), micronutrients can increase grain yield up to 50%, as well as increase macronutrient use efficiency. By supplying plants with micronutrients, either through soil application, foliar spray, or seed treatment, increased yield and higher quality, as well as macronutrient use efficiency, could be achieved. In consideration of the important role micronutrients have in promoting and maintaining human health, more research is needed to determine the advantages of using the optimum level of micronutrients instead of their critical level as an indicator with regard to yield, quality, and enrichment objectives for the future.

Key Words: Micronutrient deficiencies, calcareous soils, bicarbonate in water, crop yield and quality, crop enrichment, health promotion

Introduction

Micronutrient deficiency is widespread in plants, animals, and humans, especially in many Asian countries, due to the calcareous nature of soils, high pH, low organic matter, salt stress, continual drought, high bicarbonate content in irrigation water, and imbalanced application of fertilizers. For example, if irrigation water with an HCO_3^- concentration of 4 mEq l^{-1} (244 mg l^{-1}) is added to a field crop or an orchard at the rate of 5000 m^3 ha^{-1} $year^{-1}$, the amount of added HCO_3^- to the soil would exceed 1 ton ha^{-1} $year^{-1}$ (about 1220 kg ha^{-1}). The following equations show why high pH and high bicarbonate levels reduce the availability of micronutrients in calcareous soil:

$$CaCO_3 + H_2O \Leftrightarrow Ca\ (OH)_2 + CO_2$$

$$CaCO_3 + H_2O \Leftrightarrow HCO^-_3 + Ca^{++} + OH^-$$

$$CaCO_3 + H_2O + CO_2 \Leftrightarrow 2HCO^-_3 + Ca^{++}$$

$$CaCO_3 + 2H^+ \Leftrightarrow 2HCO^-_3$$

$$HCO^-_3 \Leftrightarrow CO^{\uparrow}_2 + OH^-$$

$$2OH^- + M^{++} \Leftrightarrow M\ (OH)_{2\downarrow};$$

where M^{++} is a micronutrient. As a result of producing more HCO_3^- and OH^- in the rhizosphere, the pH of the soil solution and, consequently, the pH of plant sap can increase to a level that causes micronutrients to precipitate, lowering the level of their availability as a whole. Ali-Ehyaee (2001) studied the status of micronutrients in the soils of 4 provinces in Iran and reported that there is a negative relationship between the percentage of soil organic matter and micronutrient deficiency.

Sillanpaa's (1990) broad study conducted in several countries revealed that crop yield, or soil and plant

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analytical data, or a combination of both indicated some degree of micronutrient deficiency, especially Zn, at all Iraqi and Pakistani study sites. In the most acute case of Zn deficiency, rice yield was more than tripled by the application of 12 kg of Zn ha^{-1}. Zn deficiency was more frequent than that of any of the other 6 micronutrients included in the study. Some degree of Zn deficiency was estimated to exist at almost 50% of the sites investigated. The occurrence of Zn deficiency was highest in Iraq and Pakistan (at almost every study site), followed by Nepal, Turkey, and Thailand, whereas it occurred with the lowest frequency in Tanzania, Finland, Zaire, and Zambia. These findings are in good agreement with analytical data subsequently collected from the same countries, especially those for calcareous soil in Iran (Malakouti and Tehrani, 2005). The reported frequencies of Zn deficiency might have partly been due to the fact that crops susceptible to Zn deficiency, such as rice and maize, were important crops for many of the countries in which the studies were conducted, and consequently, they were often selected as test crops. The response of crops to Zn varied widely, and in an extreme case no grain yield was obtained without the application of Zn. In addition, there were a number of sites in which the application of Zn did not affect the yield quantitatively, but Zn content in the soil and plants were low enough to indicate problems for animal nutrition. Although some high levels of Zn in soils and plants were measured, no clear evidence of Zn toxicity to crops was found. The percentage of nutrient-deficient soils among the 190 soils tested in 15 countries is shown in Table 1 (Sillanpaa, 1990).

Improving Crop Yield and Quality with Micronutrients

Plant, animal, and human micronutrient requirements are rather low, which is why they are called microelements; however, they are essential for vital cell functions. Micronutrient deficiency can greatly disturb plant yield and quality, and the health of domestic animals and humans (Cakmak, 2002; Welch, 2003; Malakouti, 2007). Extensive research on the effects of micronutrient fertilizers on crop yield and quality has been conducted during the past decade (Malakouti et al., 2005). Results of a broad-based study conducted in 815 irrigated wheat growing regions of Iran between 1995 and 96 in order to evaluate the effect of micronutrients on increasing wheat grain yield are presented in Table 2. The addition of each micronutrient (Fe, Zn, Cu, and B) or a combination of Fe + Zn + Cu + B to NPK fertilizer increased grain yield. The highest yield was obtained by adding all the micronutrients to NPK fertilizer (Malakouti, 2000).

Table 1. Percentage of nutrient-deficient soils among 190 tested soils (Sillanpaa, 1990).

Estimate of deficiency	Nutrient (%)								
	N	P	K	Fe	Mn	Zn	Cu	B	Mo
Acute	71	55	36	0	1	25	4	10	3
Latent[a]	14	18	19	3	9	24	10	21	12
Total	85	73	55	3	10	49	14	31	15

[a]Soils low in a nutrient, but non-responsive due to some other limiting factors or to non-susceptibility of the test crop.

Table 2. Average wheat grain yield in some 815 fields in response to the addition of micronutrients.

Treatments					
NPK	NPK + Fe	NPK + Zn	NPK + Cu	NPK + B	NPK + Fe + Zn + Cu + B
Grain yield (kg ha^{-1})					
4600	5000	5055	4900	4800	5100
Yield Increase (%)	9	10	7	4	11

Results of the study revealed that if only 1 micronutrient were to be added to calcareous soils, Zn is obviously the best choice for yield improvement (Malakoutiu, 2007). A similar experiment carried out in 433 irrigated wheat fields the following year also showed that the addition of Fe or Zn to NPK fertilizers could increase wheat grain yield, as seen in Table 3. The effect of micronutrients on increasing wheat grain yield was previously observed during 1997-98 in 331 wheat fields in Iran, where it was demonstrated that the addition of micronutrients to NPK fertilizer increased the yield of wheat grain under irrigated condition. Thus, the application of micronutrient-enriched NPK fertilizers provide a double benefit: increasing grain yield and improving the nutritional quality of the harvested grains, since micronutrient-enriched NPK fertilizers also increase the concentration of micronutrients in grain. Another experiment carried out in the Karaj region of Iran to test the ability of micronutrients to improve the yield of wheat grain also showed that grain yield increased from 3910 kg ha^{-1} to as much as 4926 kg ha^{-1}, a 26% increase (Malakouti, 2000). Researchers from the Iranian Soil and Water Research Institute evaluated the effect of zinc sulfate on the yield of rainfed wheat grain during the 1996-97 growing season and succeeded in increasing the yield from 1135 kg ha^{-1} (farmers' conventional method) to 1241 kg ha^{-1} by applying zinc sulfate. The yield increase averaged 9% in this experiment.

As reported by Malakouti and Tehrani (2005), researchers from the Iranian Soil and Water Research Institute conducted 2 experiments. In the first experiment conducted with canola plants, they found that the addition of micronutrients increased yield (Table 4). In the second experiment conducted with potato and sugar beet in 5 Iranian provinces, they concluded that balanced fertilization of potato and sugar beet gave good results in terms of the average yield of 20 fields in each of the 5 provinces (Table 5).

It was commonly believed that the thousand-kernel weight index was genetically determined, and that nutrient management would not affect this parameter in wheat. This notion was tested in a greenhouse and fields between 1996 and 1998 (Malakouti et al., 2005). The results revealed that the thousand-kernel weight index increased from 44.0 g to 48.4 g pot^{-1} (10% increase) due to balanced fertilization, and that grain yield increased from 7.1 g to 8.3 g pot^{-1}, an increase of 17%, which is significant at the α = 1% level, in the greenhouse experiment. The field experiment also showed a mean

Table 3. Average grain yield in response to balanced fertilization, according to year.

Year	No. of wheat fields	NPK	NPK + Fe	NPK+ Zn
1996-97	433	4583	4906	4989
% Yield increase		-	7	9
1997-98	331	4319	4498	4564
% Yield increase		-	4	6

Table 4. Average canola yield (kg ha^{-1}) in response to Fe and Zn fertilizers.

Study Site No.	Treatment		Yield Increase (%)	Study Site No.	Treatment		Yield increase (%)
	NPK	NPK + Fe			NPK	NPK + Zn	
1	2051	2578	26	1	3221	3513	9
2	1043	1437	38	2	2467	3169	28
3	2403	3221	34	3	1409	1579	12
4	3036	3694	22	4	2243	3816	70
5	2831	3334	18	5	2051	2578	26
Mean	2273	2853	28	6 Mean	2278	2931	29

Table 5. Average potato and sugar beet yield (kg ha^{-1}) in response to the addition of micronutrients, according to province.

Potato field location	Treatment		Yield increase (%)	Sugar beet field location	Treatment		Yield increase (%)
	NPK	NPK + Micronutrients			NPK	NPK + Micronutrients	
Semnan	29,000	32,000	10	Fars	6497	6561	1
Hamadan	41,500	46,500	12	Khorasan	4230	4545	7
Kerman	13,900	17,500	26	Arak	9858	10,635	8
Karaj	16,900	22,100	31	Karaj	6450	7500	16
Ardabil	35,500	36,700	3				
Mean	27,360	30,960	16	Mean	6759	7310	8

yield increase from 4353 kg ha^{-1} to 4640 kg ha^{-1}, as well as an increase in mean thousand-kernel weight from 38.49 g to 38.94 g due to balanced fertilization. The effect of balanced fertilization on the mean grain yield value and on the mean thousand-kernel weight index value of different wheat cultivars tested in 140 fields are shown in Tables 6 and 7.

Table 6. The effect of balanced fertilization on grain yield and thousand-kernel weight index in greenhouse experiments (average of 25 fields with 3 replications).

Grain yield (g pot^{-1})			Weight of thousand seeds (g)		
Control	Balanced fertilization	Relative increases (%)	Control	Balanced fertilization	Relative increases (%)
7.1	8.3	17	44.0	48.4	10

Table 7. The effect of balanced fertilization on grain yield (kg ha^{-1}) and thousand-kernel weight index (average of 140 fields during a 2-year experiment in various provinces).

Region	Grain yield (kg ha^{-1})		Change (%)	C.V. (%)	Weight of a thousand seeds (g)		Change (%)***	C.V. (%)
	Control	Balanced fertilization			Control	Balanced fertilization		
Fars	3904	4476	14.5**	17.29	37.73	36.75	–2.6 ns	6.12
Hamadan	5496	6418	16.8**	7.63	36.07	37.21	+3.2**	2.38
Illam	4428	4565	3.1	6.50%	36.36	36.86	+1.4**	1.41
Esfahan	5843	6287	7.6**	11.50	40.97	42.26	+3.2**	7.05
Khuzestan	2546	2555	0.4	9.52 ns	34.91	34.71	0.6 ns	4.30
Tehran	4480	4835	7.9**	10.19	47.33	47.22	–0.2**	1.63
Zabol	2800	2877	2.8	22.69 ns	37.87	37.73	–0-4 ns	10.22
Semnan	4705	4448	-5.5	12.99 ns	43.87	41.88	–4.5*	6.69
Yazd	3698	4500	21.7**	13.52	40.61	40.97	0.9	5.16
Varamin	5200	5925	14.0**	3.73	40.87	39.87	-2.5 ns	4.74
Kordestan	5023	5387	7.3**	9.81	33.31	33.99	2.0 ns	5.43
Average	4353	4640	6.6**	10.77	38.49	38.94	1.2**	5.51

*Significant differences at the 5% level. **Significant differences at the 1% level. ***The main cause of the decrease in the thousand-kernel weight index in the field studies was the existence of some growth-limiting factors in some of the provinces, such as soil salinity.
ns: no significant differences between treatments.

In severe deficiency conditions, the yield increase could reach over 100% (Sillanpaa, 1990; Malakouti and Tehrani, 2005; Malakouti, 2007). In Kohgilouyeh and Boyerahmad provinces, wheat, rice, and grape yields increased from 3220, 4697, and 10,540 kg ha^{-1} to 4117, 7508, and 19,040 kg ha^{-1} (28%, 60%, and 81%), respectively, whereas under normal conditions, mean yield increase in wheat-rice, corn, potato-onion, and oil seeds were 15%, 30%, 25%, and 20%, respectively (Figure). In other words, the application of micronutrient fertilizers to micronutrient-deficient soils is associated with improved yield and crop quality for cereals, corn, beans, forages, and oil seeds (Malakouti and Tehrani, 2005; Malakouti, 2007).

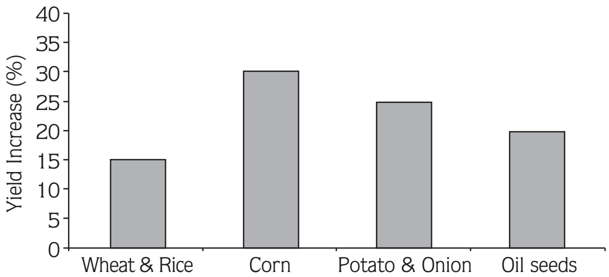

Figure. Average yield increases due to the application of micronutrients, in addition to expected improvement in crop quality and yield enrichment in calcareous soils (Malakouti and Tehrani, 2005).

Improving Fertilizer Use Efficiency with Micronutrient-fertilizers

Based on the increases in both grain yield and mineral fertilizer use efficiency, it can be suggested that use of micronutrient-enriched fertilizers results in significant economic benefit to farmers. Fertilizer use efficiency (FUE) for different crops can be increased by the application of micronutrients. It is recommended that in order to maximize FUE in crop production, micronutrient fertilizers should be applied on the basis of soil testing values in all calcareous soils. For example, according to the data in Table 5, on potato farms the average yield increase due to micronutrient fertilizer application was 13% (the average yield of potato in different provinces increased from 27,360 to 30,960 kg ha^{-1}). Then, FUE, by assuming an application rate of 50 kg of micronutrient fertilizer ha^{-1}, will be (30,960-27,360): 50 = 72 kg potato kg^{-1} of micronutrient ha^{-1} (kg ha^{-1}). Therefore, it seems more logical to practice balanced fertilization in crop production. The data from our experiments revealed that, as a whole, balanced fertilization (NPK + micronutrients), in contrast to the control (NPK), was the best (Malakouti, 2000; Malakouti and Tehrani, 2005). Mean wheat grain yields (from all 14 provinces) and mean agronomic efficiency due to balanced fertilization are given in Table 8. As with grain yield, the highest values of nitrogen use efficiency (NUE) and nitrogen apparent recovery fraction (NARF) were obtained with T_2 (balanced fertilization). The maximum recovery rates were obtained with T_2 in most sites studied. In addition to yield increases of 12%, NUE increased to 15 kg of grain kg^{-1} N and NARF increased by 36% with T_2 (Malakouti et al., 2008).

Table 8. The advantages of using balanced fertilization (T_2) for increasing average wheat yield, nitrogen use efficiency (NUE), and nitrogen apparent recovery fraction (NAR) in 22 studied sites (Malakouti et al., 2008)

Treatments Wheat grain	T_1 = Control (NPK)	T_2 = Balanced fertilization (NPK + Micronutrients)
Yield (kg ha^{-1})*	4160 B	4674 A
Protein (%)*	11.66 A	12.01 A
NUE (kg kg^{-1})	8.8 B	12.2 A
NARF (%)	23.2 B	31.6 A

* LSD for yield = 346 kg ha^{-1}. LSD for protein = 0.82%.

Discussion

The role of microelements in maintaining balanced plant physiology is becoming clearer every day as a result of studies on their reactions and the disturbances caused by their deficiency. Micronutrients are essential elements for life. Even though they are present in small amounts in plants, they activate some 100 enzymes in various plants. It is inferred that we would not be able to survive without micronutrients because they are essential to the synthesis of DNA and RNA, and to metabolizing carbohydrates, fats, proteins, and alcohols. Micronutrients also play key roles in the release of carbon dioxide, and in optimizing the function of vitamin A and the immune system (Marschner, 1995).

Calcareous soils, which are dominant in the Middle East, have high pH (7.6-8.3) and low organic matter content (< 1%) and, therefore, crops contain lower than average levels of micronutrients. Scarcity of rainfall and imbalanced fertilization also add to the problems associated with micronutrient deficiency in these regions. Plants that grow in such soils suffer from micronutrient deficiency, which is why the micronutrient concentration is below the critical level in > 80% of the crops grown in such soils. These findings correspond well to previous findings (Malakouti 1996; Cakmak, 2002; Sanchez and Swaminathan, 2005; Malakouti, 2007; Cakmak, 2008).

Micronutrient deficiency limits plant growth and affects crop yield, especially in calcareous soil. The results revealed that the application of balanced fertilization significantly increased grain yield. Field tests of more than 2500 different experiments have shown that micronutrients have a significantly positive effect on crop yield and quality. Our studies have shown that micronutrients also ensure the efficient use of macronutrients. Cakmak (2002), Malakouti (2007), Cakmak (2008), and Malakouti et al. (2008) also reported the same results.

There is an urgent need to improve the micronutrient status of calcareous soils. Despite the large body of data that clearly indicates crop productivity improves with the application of micronutrients, micronutrient fertilizers are not commonly used by farmers. This implies that there is a large gap between research, and education and extension in transferring valuable scientific information to farmers and in changing their habitual use of conventional fertilization. Despite the progress already made, more effort is still needed to increase Zn fertilizer efficiency, the awareness of environmental-related issues, and the economic aspects of micronutrients, so as to achieve sustainable agriculture for food security and human health.

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