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Review

The Efficacy of Micronutrient Fertilizers on the Yield Formulation and Quality of Wheat Grains

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Abstract: Under the changing climatic conditions, one of the most pressing issues in wheat production is the improvement of the yield quality, the lack of which has a negative impact on animal and human health. More than 25% of the world's population are affected by micronutrient deficiencies in food products, a problem which is known as hidden hunger. Thus, effective micronutrient management is crucial for improving both the quantity and quality of wheat production by increasing the plant's ability to tolerate various environmental stresses and diseases. In this review, previous works were assessed to investigate the significance of micronutrient fertilizers and their interaction effects on the wheat grain yield and quality, including high-quality and nutritionally rich products. The application of micronutrients mixed with macronutrients significantly increases plant growth, physiological traits, yield components, the grain yield, and the quality traits. Among the types of applications, the foliar application of nutrients is very profitable due to its efficiency in terms of economics, ecology, and the qualitative and quantitative yield. In short, in-depth studies are needed to determine the best concentrations, forms, and times of application of micro-fertilizers to the wheat field and to mitigate the challenges of the increasing wheat demand due to steadily rising world population growth and reducing the rates of nutritional deficiency.

Keywords: wheat; micronutrient fertilizers; nutritional deficiency; nitrate reductases

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1. Introduction

One of the most pressing problems of modern agrochemistry is the lack of available forms of micronutrients in the soil for wheat, as for any cereal crop, and their impacts on the crop yield. However, in recent years, the production of wheat grain has increased globally, but its quality has not improved, which can have a negative impact on animal and human health. Wheat is presently the most widely grown crop in the world, grown on 217 million hectares per year with a total world production exceeding 700 million tons, due to its many favorable qualities for human nutrition [1]. Grain quality is the main criterion for evaluating wheat on the world market. Indeed, the quantity and nutritional value of plant products are among the factors determining human and animal health. Already, more than 2 billion people, or 25% of the world's population, are affected by micronutrient deficiencies, a leading cause of death and disease [2,3]. We can observe the same phenomenon in the plant world.

Unfortunately, wheat is inherently low in essential dietary micronutrients for human health, which can be provided through the appropriate use of micronutrient fertilizers (MNF) [4]. To varying degrees, trace elements play a structural role and are known to be cofactors for enzymes in various bioelectric reactions in the plant life cycle. Thus, a large part of the yield quality is influenced by fertilization. In addition to nitrogen, phosphorus, potassium, magnesium, and sulfur, as well as trace elements, have decisive influences on productivity and the degree of compliance with the quality criteria.

In [5], the authors stated that the use of micronutrient fertilizers can provide substantial outcomes regarding the yield characteristics and protein content, increasing nutrient accessibility and affecting the physiological parameters of the crop, as reflected in the yield increase. Years of relying solely on NPK has resulted in soil degradation and nutritional deficits. The addition of MNF boosts crop yields and improves the effectiveness of NPK use when applied in a balanced manner with macronutrients [6]. Nevertheless, their inclusion in yield formulations to increase wheat production is limited. Deficiency in a single essential micro-nutrient (B, Cu, Fe, Mn, Mo, Ni, Zn, and Cl) can impede the plant's development and growth and cause a significant reduction in the crop yield. Additionally, the primary cause of death on earth is micronutrient-deficient food and the associated diet-related issues, which can be avoided by sustainably supplying nutrients and addressing malnutrition [7,8]. Irrespective of the lucrative aspects of this crop, wheat scientists and producers face several challenges including, but not limited to, the excessive, minimal, or lack of use of micronutrient fertilizers, which, when deficient, can be related to disease and pest incidence, as well as their severity, which affect choices and activities in wheat production [9].

In general, nutrient deficiency weakens plants, weakening their immunity and their ability to resist fungal and bacterial infections.

However, if investigated, this can be attributed to minimal or no use, the slow mobility of nutrients within plants, or excessive use. Presently, shifting weather patterns due to global climatic change and inappropriate fertilizer use, combined with environmental risks, prevent producers from achieving the desired yield, quality, and economic opportunities [10,11]. Consequently, an immense shift from the traditional approach of producers who have been responsible for food, feeding stuff production, and industrial raw materials and supporting the functioning of humans and animals and their survival in previous years is still a challenge. However, there is a need to focus on methods for increasing wheat production so as to mitigate the challenge of the increasing world population, and the use of micro-fertilizers in wheat fields must not be ignored in efforts to meet the need for yield increase and reduce nutritional deficiency worldwide [12,13]. This review summarizes the progress of research on the importance of micronutrient fertilizers in wheat production; the optimal concentrations, forms, methods of application; and their interactions in wheat fields to mitigate the challenges of nutritional deficiencies, thus serving as a reference for the minimal, excessive, or lack of use of micro-fertilizers. Moreover, less attention is paid to chlorine, which is used primarily for small grains such as wheat. Chlorine helps plants to manage water stress and resist fungal diseases.

2. The Significance of Micronutrient Fertilizers, Their Interactions, and Application Techniques in Wheat Cultivation

The micronutrient fertilizers Zn, Mn, B, Fe, Cu, and Mo are the six most essential for increasing productivity in wheat farming [14,15]. Though they account for a smaller amount, their importance in promoting the yield and yield parameters should not be ignored. Their contributions to plant nutrition and soil productivity render them more significant. Moreover, micronutrient fertilizers not only play pivotal roles in plant nutrition, the better development of grains, the improvement of physiological traits and yield parameters, and in ameliorating nutrient deficiency in wheat [16], but humans and animals also require them for their well-being [15,17]. One of the leading causes of the high prevalence of micronutrient deficiencies in human populations is the insufficient quantities and low bioavailability of micronutrients in plant-based diets. Typically, there is a spatial overlap between human populations' vitamin inadequacies and those of micronutrients in cultivated soils [18]. This suggests a close relationship between the population's health and the micronutrient status of plants. However, there is generally less concern regarding micronutrients in relation to production sustainability and the nutritional quality of food crops compared to other plant mineral requirements. According to researchers, the application of micronutrient fertilizers such as (Fe + Zn) in combination with N and K is the best option for achieving a higher grain yield and quality of wheat [19,20].

Notwithstanding the frequent and acceptable application of NPK fertilizer, ensuring the average growth of high-yielding grain varieties is challenging due to the minimal, inappropriate, or lack of inclusion of micronutrient fertilizers in wheat production. The authors of [21,22] stated that widely fluidizer-responsive varieties expressed their full yield potential when trace elements of (Zn, Fe, B) micronutrient fertilizers were applied together with NPK fertilizers, which meaningfully improved the wheat yield compared to the controls when applied singly or in a mixture with other fertilizer elements. Meanwhile, the authors of [23] also noted a positive interaction between fertilizer treatments and the physiological stages of wheat growth when micronutrient fertilizer was combined with macronutrient fertilizer. The use of micronutrient fertilizers (Boron, Copper) positively affected the wheat parameters and increased the grain yield considerably [24]. Micronutrients also play pivotal roles in chlorophyll and nucleic acid formation, protein synthesis, metabolism, and several enzymatic activities of photosynthesis, as well as respiration [25,26]. Ziaeian and Malakouti [27] reported that when micronutrient fertilizers are applied to wheat, the total uptake of Zn, Cu, Fe, and Mn in the grain and flag leaves was significantly increased. Other findings demonstrated that micronutrient fertilizers such as (Fe, Cu, Zn, B, Mn, and Mo) are required for the critical development of plants. Research has shown that small amounts of foliar-applied micronutrients (singly or combined with other essential elements) can increase the yield and its components, thus enhancing wheat growth and quality (Table 1) [28–31].

Table 1. Effects of micronutrients on the yield and quality indicators of winter wheat grain.

Micronutrient	Form/Concentration	Application Method	Yield Quantity and Quality		References
Mn	salt ($MnCl_2 \cdot 4H_2O$)	soil application	9% yield increase		[32]
	bulk ($MnCl_2 \cdot 4H_2O$)		13% yield increase		
	nano (Mn_2O_3)		16% yield increase		
	nano (Mn_2O_3)	foliar application	22% yield increase		
Mn	Mn ($MnSO_4$): 0.1 and 0.01 M	seed treatment	3.87 increase in Mg ha^{-1}	increase in the Mn concentration of the grains	[33]
	Mn ($MnSO_4$): 250 and 500 mg Mn kg^{-1}		3.57 increase in Mg ha^{-1}		
	a 0.75 M solution of Mn ($MnSO_4$)	foliar application	3.74 increase in Mg ha^{-1}		
Cu	NPK + Cu	foliar application	increased content of Cu and glutenins in the grain		[34]
Zn	Zn + NPK				
Cu + Zn + Mn	NPK + (Cu + Zn + Mn)		increase in the contents of Cu, Zn, gliadins, and glutenins in the grain		
Mn	Mn + NPK		increase in the Fe content in gliadin fractions, as well as glutenins		
Mn	Mn at 1.5 kg ha^{-1}	foliar application	increase in the Zn and Fe contents in the grain		[35]
Zn + Fe	nutrient mixture (Zn+ Fe)		improved spike length, number of spikelets /spike, number of spike/m^2, number of tillers/m^2, number of grains/spike, 1000-grain weight		
Mo	Mo [$(NH)_6Mo_7O_{24} \cdot 4H_2O$] + NH_4^+, NO_3^- and NH_4NO_3	soil application	Mo increased N uptake efficiency in wheat		[36]
Mo	Mo 40 g ha^{-1}	seed treatment	wheat seed yield increased with increasing N levels in the top dressing		[37]
		foliar application			
	each at 20 g ha^{-1}	seed + foliar application			
Mo	Mo [$(NH_4)_2MoO_4$]	soil application	increased the grain yield of winter wheat, the number of ears, and the weight per thousand grains		[38]
Zn	Zn ($ZnSO_4$)				
Mo + Zn	Mo [$(NH_4)_2MoO_4$] + Zn ($ZnSO_4$)				

Table 1. *Cont.*

Micronutrient	Form/Concentration	Application Method	Yield Quantity and Quality	References
Zn	compost 10 t ha^{-1} + 10.0 kg Zn ha^{-1}	soil application	improved the plant height (8.08%), tillers/m^2 (21.61%), spikes/m^2 (22.33%), and spike length (40.50%), as well as an increased yield (18.37%) compared to control	[39]
	($ZnSO_4$) (4%, 6%)	foliar application	6% zinc application for improved plant growth, yield-related traits, and nutritional quality	[40]
Zn-Se	1.5 kg Zn ha^{-1} ($ZnSO_4$) + 10 g Se ha^{-1} (Na_2SeO_4) + N (0, 105, 140, 180 kg N ha^{-1})	foliar application	foliar Zn-Se application had a substantial positive effect on the Zn and Se grain concentrations, while the grain Fe, P, and Cd concentrations decreased under foliar Zn-Se application	[41]
Zn + Fe,	Zn + Fe, Zn, Fe (Zn-EDTA and Fe-EDTA)	foliar application	combined foliar application of Zn and Fe increased the grain Zn and Fe, thus alleviating the adverse effects of water stress on all wheat ploidy levels, making biofortification cost-effective	[31]
B	B (50 ppm) in booting growth stage or in anthesis stage	foliar application	the mean values obtained for the boron application time were a potential contributor to the total grain mass by improving the plant height, spike length, number of spikelets, grain yield $plant^{-1}$, 1000-grain weight, and grain yield ha^{-1}. Foliar boron application in the booting stage (B_1) under normal irrigation levels (I_3 = 100% wheat water requirement) produced the highest recorded values for all the studied trades	[42]
B	B-coated urea and B coating + fertilizer urea nitrogen	seed treatment	the boron-coated urea (0.5% B) increased the leaf area index (30.2%), spike length (12.5%), number of spikes (10.9%), filled grains (15.7%), and grain weight (16.3%) per spike. Furthermore, the grain and straw yields of spring wheat increased by 11% and 10.6%, respectively, as compared to uncoated prilled urea. It also increased the N concentration and N uptake in both wheat grain and straw. The net returns (USD915.1 ha^{-1}) and benefit:cost ratio (1.40) were also the highest with 0.5% boron-coated urea, being significantly higher than uncoated prilled urea	[43]
B	calcium sulfate (4 mM and 8 mM), potassium sulfate (2% and 4%), and borax (10 mg and 20 mg)	foliar application	the foliar spray of calcium, potassium, and boron enhanced the plant height, plant biomass, and the amount of chlorophyll synthesis, as well as thew yield, thus reducing the negative effects of drought	[44]
Zn + Fe	Zn ($ZnSO_4H\ _2O$) and Fe ($FeSO_47H_2O$): 100% Zn, 80% Zn + 20% Fe, 60% Zn + 40% Fe, 40% Zn + 60% Fe, 20% Zn + 80% Fe, and 100% Fe.	foliar application	grain crude fat content remained unaffected. Crude fiber was enhanced up to three-fold by 60% Zn + 40% Fe5.5 (5.5 kg ha^{-1} of 60% Zn + 40% Fe). Moreover, 80% Zn + 20% Fe5.5 (5.5 kg ha^{-1} of 80% Zn + 20% Fe) was the best combination for increasing the crude protein. Zinc applied alone enhanced the Zn concentration in grain	[13]

Micronutrient fertilizers are crucial for N metabolism and have many interactions with other nutrients and several macronutrients. Dietary imbalances cause deficiencies more frequently than a shortage of a specific vitamin. Micronutrients interact significantly with other mineral nutrients, as in the interaction of inorganic phosphate (Pi) with Zn and Fe [45–47]. Root Zn absorption is inhibited by high Pi levels [48,49]. In contrast, Zn shortage boosts Pi uptake [50]. N fertilization favors Zn and Fe root uptake, root-to-shoot transfer, and remobilization [51]. In agreement with this finding, seeds' Zn, Fe, and protein concentrations and localizations are all strongly connected [52]. On the other hand, sulfur (S) fertilization significantly negatively affects Mo uptake, leading to Mo deficiency [53,54]. To determine the molecular bases of these interactions, it is necessary to understand the functions of the relevant metalloproteins so as to ascertain the molecular underpinnings of these interactions.

Zn is known to be a critical element and serve as a metal component of enzymes or as a functional, structural, or regulatory cofactor of many enzymes [26,55]. Copper (Cu) is an enzyme activator and plays essential roles in the absorption of N compounds and, indirectly, in chlorophyll production, increasing the sugar contents. Manganese (Mn) and Zinc (Zn) influence protein biosynthesis by adjusting the activity of peptidases and controlling protein metabolism [56,57]. Iron (Fe) promotes the formation of chlorophyll and the enzyme mechanism, which works with the respiratory systems of cells and plays a role in cell division and growth [19,29,56,58].

Micronutrient fertilizers are applied via various techniques, including seed priming, soil treatment, foliar application, side dressing, and fortification (Table 1). However, the foliar application is the most advantageous according to [25]. Arif et al. [58] claimed that the foliar treatment of ferrous sulfate was superior to soil application for the treatment of Fe chlorosis in wheat. Both macronutrient and micronutrient fertilizers were foliar-applied, and the wheat output was significantly enhanced [58]. According to [59], foliar micronutrient fertilizers boosted the wheat yield and increased the uptake of both macro- and micronutrients.

The results of [60] indicated that foliar treatment with boron (B) increases the protein percentage of seed and yield components. Nadim et al. [61] illustrated that the micronutrient fertilizer B had a critical interaction with application methods based on side dressing for the grain yield, effectively producing a higher number of tillers, grains per spike, and grain yield. This method showed a better combination with iron for a higher number of tillers and grain yield. Gomaa et al. [29] also reported that the soil application of micronutrients combined with macronutrient fertilizers had a positive effect on the grain yield and yield components, including the harvest index, which was enhanced more significantly by soil application than foliar application. Earlier studies indicated that this increase might occur due to the efficient utilization of nutrients in the soil, which enhances the number of tillers/m^2, the number of spikes/m^2, and the number of grains/spike [62]. Similar results, more or less, were obtained by the authors of [35,58,61,63]. According to [64,65], the foliar application of micronutrient fertilizers represents a method of providing nutrients to a higher number of plants more efficiently than methods involving soil application when the soil conditions are not suitable for Fe availability. Nasiri et al. [66] claimed that the foliar application of micronutrient fertilizers resulted in quick absorption by the leaf epidermis and accessibility to other plant parts through the xylem and phloem.

Due to a high reliance on synthetic fertilizers and increased cropping intensity in the case of high-yielding varieties, soil micronutrient fertilizer depletion is rapid [67]. According to the WHO, Zn deficiency in underdeveloped nations ranks as the fifth leading cause of human disease and death [68]. Through biofortification, the foliar spraying of micronutrient fertilizers can augment their concentration. Torun et al. [69] demonstrated that fertilizing with zinc enhanced wheat and rape seed yields and improved the grains' zinc content. Additionally, Mn, Zn, Fe, and Cu (singly or in combination) significantly increased the rice yield [70], while the application of Zn also increased the maize yield [71]. Zinc used in maize is highly influenced by nitrogen metabolism, protein quality, chlorophyll production, and photosynthesis. Numerous studies have evaluated how wheat responds to the application of micronutrient fertilizers (seed, soil, foliar-applied) (Table 1). A combination of macronutrient and micronutrient fertilizers in wheat production still needs to be further explored using various yield formulation techniques, modes, and timings.

3. The Effect of Micronutrient Fertilizers on Growth and Yield Attributes in Wheat Production

3.1. Zinc (Zn)

Zinc fertilizer is essential for increasing fertility (number of grains/ear) and improving the grain quality. It aids in the promotion of more robust emergence, quicker stand establishment, healthier root growth, greater plant vigor, and a higher yield [72]. Zinc is necessary for protein synthesis, plant metabolism, and N metabolic activity, and its absence can impair protein synthesis in plants. Moreover, Zn deficiency in humans causes dysfunction of the reproductive system, anorexia, immune disorders, and skin lesions and negatively affects brain development [73,74]. Cereal-based farming systems often have soils with deficiencies in zinc, and this insufficiency impairs root growth, physiological functions, and nutrient uptake, causing irregular light brown lesions with dark brown margins, resulting in grain yield and yield parameter reductions (Figure 1). Grain nutritional value can be reduced by zinc insufficiency, a common micronutrient shortage in wheat. Zinc deficiency is a significant global risk factor for human health and a leading cause of death Cakmak, 2002 [4,75].

(**A**) Head sterility of B-deficient plants (right). Normal heads on the left.

(**B**) Frost damage of the head is sometimes confused with Cu deficiency.

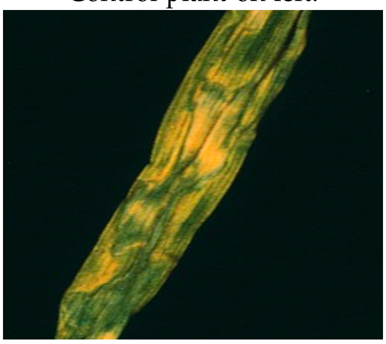
(**C**) Fe deficiency. Interveinal chlorosis. Control leaf on left.

(**D**) Cu deficiency in the field, showing discoloration in the stubble.

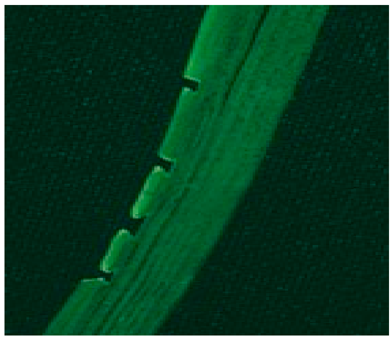
(**E**) Note symptoms on new and middle-aged leaves. Control plant on left.

(**F**) Longitudinal yellow striping is a characteristic of Mo deficiency. Control leaf on the left.

(**G**) Mo deficiency (left) shows delayed maturity and white heads.



(**H**) Close-up of Zn-deficient leaf showing mottling and necrotic lesions.



(**I**) Saw-tooth effect and splitting near the mid-rib, attributed to B deficiency.

Figure 1. Nutrient Deficiency Symptoms in wheat, adapted from [76].

Worldwide, Zn insufficiency, limiting its availability to plants, now affects over 50% of cultivated soils used to grow wheat and is ranked 5th among the 10 most crucial risk factors in developing nations and 11th among the top risk 20 factors globally, according to a WHO assessment from 2002, for illnesses and disorders [77]. A thorough investigation by the authors of [78] found that Zn deficiency affects, on average, one-third of the world's population, varying from 4 to 73% across different nations.

Zn deficiencies are common in Southern European and Mediterranean countries, though they often go undetected in plants [14,79].

Epstein and Bloom [80] conducted an experiment which showed that when Zn was omitted, its deficiency adversely affected plant flowering and fruit development. Due to low soil levels, trace nutrients such as zinc may impede wheat production [81]. Gomaa et al. [29] revealed that a mixture of micro-fertilizers (Zn + Fe) produced the highest yield and component values, chemical compositions, and quantitative and technological values of wheat grain. Firdous et al. [82] also confirmed a significant increase in the grain yield after the application of Zinc at 5kg/ha + 2 foliar sprays, with an average gain yield of 3.93 t/ha. According to Arafat et al. [83], Zn was applied at a rate of 10.50 kg/ha, and a grain yield of 4.27 t/ha was achieved with a side dressing application method. Thus, the yield and yield components increased under the existing agro-climatic conditions.

Malakouti [84] indicated that zinc fertilizers are nutrients that can be applied to plants as a side dressing, foliar application, or broadcast application to improve the wheat quality and yield. Based on the research conducted by Tao et al. [85], adding zinc to the soil before the cultivation of wheat can enhance the quality of wheat flour by reducing the negative consequences of high-temperature stress (HTS) on the yield, protein content, and component content. Similar findings obtained by Habib et al. [86] suggest that the foliar application of Zn and Fe boosted the seed yield and quality compared to the control, thus producing the highest grain yield and a superior flour quality compared to other treatments and reducing the harmful effects of HTS. Firdous et al. [82] concluded that using micronutrient fertilizers in the cultivation zone of wheat might not be sufficient to meet the crop's requirements. According to their findings, using micronutrient fertilizers as foliar sprays is an alternative method. Firdous et al. [82] demonstrated that the foliar application of micronutrients is just as efficient as soil application. The use of micronutrients, particularly Zn and Fe, increases the grain output and enhances the seed quality [87]. This is a clear example of agronomic biofortification, which results in the improvement of both quantitative and qualitative food security. Hassan et al. [88] demonstrated the pragmatism of agronomic biofortification for micronutrients in bread wheat. Their research revealed that foliar application had the best biofortification effect compared to soil application and seed priming. However, soil application led to the greatest wheat productivity. Therefore, to achieve optimal zinc biofortification whilst maintaining high wheat productivity, it is prudent to implement bimodal application, viz., foliar and soil application of the micronutrient. Velu et al. [89] agreed with these findings and postulated that combining foliar and soil applications has the potential to increase the wheat grain zinc concentration by 3-fold. However, the method has its limitations, as in cases where the grain iron concentration is concerned. Iron is less mobile in the phloems of the wheat plant; hence, different forms of both and inorganic iron fertilizers seem to have no effect on the grain concentration in durum wheat [4]. The supply of micronutrients through nanofertilizers has been illustrated to have a positive impact on the uptake micronutrients, such as iron. The iron translocation levels are enhanced. This has an advantageous effect on the photosynthetic activity of the plant. The foliar application of Zinc oxide (ZnO) increases the grain protein content as well as the photosynthetic pigments. The use of nanomaterials in the supply of micronutrients to the wheat crop ensures that the proper fertilizer doses are applied at the appropriate time. This, therefore, reduces the environmental risks whilst improving nutrient uptake and absorption. However, nanofertilizers, viz., ZnO, may have lethal effects as a result of increased reactivity resulting from the size to surface area ratio, i.e., the small size and large surface area [90].

3.2. Iron (Fe)

Iron is critical for healthy green foliage (chlorophyll) and an increased yield and quality of wheat. Thus, it is a part of most enzymes, and a specific pigment processes and helps the plant to produce energy by reducing the levels of nitrate and sulfate (Table 2). Iron deficiency causes interveinal chlorosis because of insufficient chlorophyll production, with distinctive yellow-green stripes on young leaves (Figure 1). If it is not corrected, the leaf blade will turn yellow, and the chlorosis will spread to the older leaves. The iron rate of plant tissues ranges from 200 to 400 ppm. In healthy plants, however, the rate must be greater than 100ppm, thus showing no signs of chlorosis, which typically appears in young leaves as the primary symptom [91]. Fe forms part of cytochromes and electron transport systems, and as such, it is essential for chlorophyll production in plants [92]. Hydrogen carbonate (HCO_3) inhibits Fe absorption by inducing Fe chlorosis [93]. Similarly, Fe deficiencies are common in Southern European and Mediterranean countries and most calcareous soils, though they do not always cause visible symptoms in plants [14,79]. Additionally, the application of trace elements has been the subject of many studies around the globe. The findings of Ziaeian and Malakouti revealed that the use of trace micronutrient concentrations increased the yield quantity and quality of wheat grains [27]. Congruent results obtained by [84,94] showed that the use of individual elements (Fe, Zn, Cu, and B) or a combination of Fe + Zn + Cu + B with NPK fertilizer enhanced grain production.

Table 2. Micronutrients required for healthy plant growth, their roles in plant metabolism, and symptoms associated with their deficiencies.

Micronutrient	Pathway	Enzymes	Symptom	Source	Deficiency
Copper (Cu)	Electron transport	Ascorbic acid oxidase, tyrosinase, monoamine oxidase, uricase, cytochrome oxidase, phenolate, laccase, and plastocyanin	Copper is immobile, which means that deficiency symptoms occur in the new leaves. Note that these manifest differently depending on the crop. Typically, symptoms start with a bulging and slight chlorosis of the leaf or appear between the veins of the new leaves.	Cu^{2+}	• Small necrotic spots may form on the chlorotic areas of the leaf, especially on the leaf margins. • As symptoms progress, new leaves become smaller, lose their luster, and may wither in some cases. • Apical meristems may become necrotic and die, inhibiting the growth of lateral branches.
Chlorine (Cl)	Photosynthetic reactions		Poor germination, chlorosis, and necrotic lesions.	Cl^{-}	• Leaves show variegated chlorosis followed by necrosis. • Fruit formation is reduced, and the size of the fruit is also reduced.
Manganese (Mn)	Respiration	Some dehydrogenases, decarboxylases, kinases, oxidases, and peroxidases	Reduced sugar and cellulose contents, increased drought sensitivity, reduced fertility.	Mn^{2+}	• Interveinal chlorosis. • Grey specks and streaks. • Legume cotyledons with brownish spots. • Stunted growth. • Manganese is very immobile in plants; thus, deficiency symptoms appear first on younger leaves, with yellowing between the veins. Sometimes a series of brownish-black specks appear.
Nickel (NI)	Catalyst in enzymes used to help legumes, fixes nitrogen.	Urease and hydrogenases	Impeded use of nitrogenous fertilizers. Nickel deficiency causes urea toxicity.	Ni^{2+}	• Leaves show variegated chlorosis followed by necrosis. • Fruit formation is reduced, and the size of the fruit is also reduced.

Table 2. *Cont.*

Micronutrient	Pathway	Enzymes	Symptom	Source	Deficiency
Molybdenum (Mo)	Nitrogen use	Nitrogenase, nitrogen reductase	The symptoms of molybdenum deficiency are similar to those of nitrogen (chlorosis) or sulfur deficiency. The main symptoms are reduced growth and pale green foliage.	$HMoO_4^-$ MoO_4^{2-}	• Deficient plants become stunted and lack vigor. • The entire leaf becomes pale, and marginal necrosis may also occur. • Browning of the leaf margins is sometimes observed. • Leaves may be deformed, and in the case of cauliflower, a deficiency may cause a "whip stem" to form. • In legumes, deficiency reduces nodule formation. In cauliflower, the leaves first curl up into a "spoon". • In more advanced cases, plant growth and flower formation are limited. • In cases of very severe deficiency, the plant remains dwarfed, with a progressive drying of the leaf margins. • The dead tissues turn brown and fold upwards. • The crops most susceptible to molybdenum deficiency are crucifers (broccoli, cauliflower, cabbage), legumes (beans, peas, clovers), poinsettias, and primroses.
Boron (B)	Cell division, growth, and membrane function	Synthesis of uracil, cell wall structure	Problems related to cell wall formation, including reduced shoot and root growth, infertility.	BO_3^- or $B_4O_7^{2-}$	• B deficiency often affects terminal buds, flowers, and fruits. It is not very mobile in the soil. • There is degeneration of the roots and young shoots, as well as drying of young leaves. • The cause seems to be a lack of assimilate supply and a disturbance of the water balance. • There is an exaggerated development of lateral buds caused by the lack of apical dominance of the plants. • The flowering and the fruit-setting are hindered. • There is a high transpiration which negatively influences the water balance.
Zinc (Zn)	Electron transport and auxin biosynthesis	Alcohol dehydrogenase, glutamic dehydrogenase, and carbonic anhydrase	Like most micronutrients, zinc is immobile, which means that its deficiency symptoms (interveinal chlorosis and necrosis,) occur in new leaves.	Zn^{2+}	• Symptoms due to deficiency are as follows: necrotic spots may form on leaf margins or tips; new leaves are smaller and are often bulging or distorted; bud development is poor, reducing flowering and branching; internodes shrink, giving the plant a rosette appearance; and reduced disease resistance.

Table 2. *Cont.*

Micronutrient	Pathway	Enzymes	Symptom	Source	Deficiency
Iron (Fe)		Plants absorb iron from the soil through ferric ions (Fe +++). It plays a vital role in cell division, respiration, and different steps involved in the electron transport system. It is an essential constituent of cytochrome and ferredoxin and acts as an activator of aconitase, catalase, peroxidase, and some Krebs cycle enzymes. It aids in chlorophyll synthesis but is not part of chlorophyll molecules. It is found as a fixed protein (phytoferritin) in leaves and the chromatin network of the nucleus. In metabolic reactions, it participates as Fe ++(Ferrous).	Young leaves show extensive chlorosis and may become white or yellow-white. The derailment of the reactions of photosynthesis, respiration, and protein synthesis occurs. Cell division activity is inhibited. Plant growth becomes slow.	Fe^{3+} (mostly) Fe^{2+} (mostly acidic soils)	• Young leaves show extensive chlorosis and may become white or yellow-white. • The derailment of the reactions of photosynthesis, respiration, and protein synthesis occurs. • Cell division activity is inhibited. • Plant growth becomes slow.

Adapted from [95,96].

Abbas et al. [97] applied Fe at 12 kg/ha^{-1} with the recommended NPK and reported that the grain yield improved as the rate of Fe application increased up to 12 kg/ha, but more significant rates of Fe had no discernible impact. Observations in an experiment undertaken by the authors of [20] exhibited that the application of Fe alone produced the highest starch contents. Niyigaba et al. [13] illustrated that the optimal method for increasing Fe in grain was 100% Fe 13 (13 kg ha^{-1}). To boost the Fe concentration and improve the wheat grain quality, the foliar application of Fe is essential. When paired with Zn, it was found to be a realistic strategy. Additionally, all Fe-containing treatments demonstrated high yields, the grain crude fat content was unaltered, and the crude fiber was enhanced using 60% Zn + 40% Fe 5.5 (5.5 kg ha^{-1} of 60% Zn + 40% Fe) by up to three times (Table 1) [13].

Regarding Fe and Zn, cereals can supply up to 60% and 52% of one's daily micronutrient requirements, respectively [98]. Micronutrient Fe applied as fertilizer not only increases the grain yield and quality in wheat production but also mitigates Fe deficiency by reducing the scale of the problem of Fe deficiency anemia, especially in malnourished children worldwide. Thus, this nutrient deficiency can have severe effects on human health, regrettably resulting in a substantial global health burden, particularly for women and young children in underdeveloped nations [4,75]. This is an area of concern in wheat production, since wheat is ranked as the most widely consumed cereal in the world.

3.3. Boron (B)

Boron is another vital micronutrient fertilizer for wheat and humans who consume the crop. B plays essential roles in the production of cell walls, plasma membrane maintenance, cell wall division, increasing the photosynthetic rate and transport, pod formation, nodule population, and grain quality [99]. Boron is not mobile within plants; thus, it is crucial to maintain its level throughout the growing season, especially during ear development and anthesis [100]. The mechanisms of flowering and fruiting, cell division, calcium consumption, osmotic adjustment, disease resistance, nitrogen metabolism, and the catalyzation of many reactions all involve the element boron [101]. Boron is required during the reproductive and vegetative stages because it aids in seed germination and grain formation.

Boron deficiency was first observed in Australia, Egypt, France, Poland, Taiwan, the United States, Russia, and Ukraine. That is why boron fertilizers are used more widely than other micro-fertilizers in developed countries [102]. Boron deficiency is becoming more common in cereals. However, the requirement for boron is relatively low compared to other micro-fertilizers. Both boron toxicity and deficiency reduce crop output and the life cycle of plants by causing poor grain sets, leading to a poor yield [103]. The absence of boron in any developmental stage of wheat results in aborted pollen grains, a reduced seed quality, fewer grains per spike, and other problems (Figure 1) [104,105]. The results of the research undertaken by Brdar-Jokanovi et al. [106] showed that the consequences of B nutrition disorder are more noticeable in species in which the element is phloem-immobile and during plant reproduction.

Tefera [107] indicated that boron, sulfur, and zinc fertilizer rank amongst the topmost soil map-based fertilizers in testing. According to Abdisa et al. [99], the highest yield of bread wheat was obtained with 200 kg/ha^{-1} of chemically blended boron, nitrogen, phosphorus, and sulfur, with 112.2 kg/ha^{-1} nitrogen, rather than the application of any straight and complex fertilizer having only macronutrients. Similarly, studies have confirmed that adding B, Fe, and Z to the soil, seed treatment, and foliar application significantly improved the growth, yield, and yield components [63,108]. Firdous et al. (2018) stated that the application of boron considerably increased the wheat output. The treatment based on 1 kg B ha^{-1} soil application was combined with two foliar sprays in the pre-flowering and panicle initiation stages, and the highest grain yield of 3.93 t ha^{-1} was attained [82].

According to recent research [109], there is growing evidence to suggest that using micro-fertilizers B alone or in combination with macro-fertilizers considerably improves plant growth, physiological attributes, yield components, and most grain quality traits, with focuses on health areas in which boron might be involved, such as osteoarthritis, bone health, and cancer. Desta [109] asserted the significance of these micronutrients, but fertilizer advice must be site- and context-specific, considering the soil studied, thus marking the essence of soil testing before B application to any soil site.

3.4. Copper (Cu)

Copper (Cu) is an essential micronutrient fertilizer for plant growth and metabolism, as well as an antimicrobial property used in crop and livestock production. Cu enhances chlorophyll and seed formation, photosynthesis, and the photolysis of water and is used in enzymatic reactions required for crop growth and as a cofactor of various proteins (Table 2). Plants with sufficient Cu can resist fungal attacks due to their more muscular cell walls (Figure 1) [110].

Cu deficiency reduced growth and caused the distortion of the younger leaves and necrosis of the apical meristem [111]. Cu increases fertility in wheat (number of grains/ear) and results in a better grain quality (Table 1). In cases of deficiency, adding copper sulfate individually or as part of a micronutrient fertilizer mixture is vital to soil or foliar feeding. Copper sulfate meets the organic crop production standards because it is naturally occurring. Recent studies investigated the use of Cu-based fertilizers as prospective nano pesticides or nano fertilizers. The results were an increased crop yield, enhanced nutrition of the edible tissues, amelioration of photosynthesis, accentuation of respiration, improved carbohydrate synthesis, boosted protein metabolism, and reduced disease risks [112,113]. Copper oxide nanoparticle fertilizers (CuO) are among the most widely used micronutrient fertilizers and have promising emerging applications in agriculture [114,115]. According to Karamanos et al. [116], spreading and incorporating Cu in the form of $CuSO_4{\cdot}5H_2O$ always produced the highest grain yield of wheat. Their results supported prior findings reported in [117], indicating that the soil application of at least 4 kg $CuSO_4{\cdot}5H_2O$-Cu ha^{-1} resulted in the maximum grain yield by addressing the Cu shortage. The authors thus claimed that a single foliar application of Cu at Feekes growth stage 6 provided a satisfactory grain yield increase; however, it may have to be supplemented with a second application at Feekes growth stage 10 to obtain the maximum grain yield. Miloudi and Masmoudi [118], as well as Mekkei and Eman [119], reported that a combined foliar treatment of micronutrients (Cu, Fe, Mn, and Zn) stimulated most of the yield parameters, the grain yield, 1000 g weight, straw yield, biological yield, and harvest index. Similarly, Khan [120] claimed that micronutrient fertilizers gradually increased the number of grains per spike, 1000 g weight, straw yield, and biological yield; however, there was no pronounced effect on the spike length. In contrast to untreated wheat, the foliar application of chelated copper from several sources considerably boosted all the growth and yield parameters, as well as the straw and biological products [121].

Kumar et al. [122] disclosed that increasing the amount of copper applied improved its concentration in the leaves and dry matter output. Studies conductyed by Ziaeian and Malakouti [27] showed that the application of Cu and other micronutrients significantly boosted their concentrations and absorption in grain and flag leaves, hence increasing the grain protein content. Similarly, Azhar et al. [123] reported the beneficial effects of using a foliar application of copper, either as Cu-EDTA or Cu-amino acids, on wheat growth parameters, which can be attributed to the essential role of copper, therefore, increasing the yield and protein content. Findings obtained by Zain et al. [124] showed that wheat plants treated with micronutrients showed significantly higher morphological, physiological, and production metrics when compared to the controls. The urgent need to improve crop yields is increasing, and researchers are continually exploring ways to maintain global food security in light of an estimated population of over 9 billion by 2050. Hence, the inclusion of Cu in fertilization systems for wheat production is vital.

3.5. Molybdenum (Mo)

Mo is an essential micro-fertilizer that is required for most plant tissues and serves as a base allowing for all other nutrients to be equated and quantified. Molybdenum fertilizer is efficient for Nitrate and P metabolism in wheat and vital for enhancing the yield, growth parameters, and yield components. For plants to absorb, assimilate, and transport nitrogen (N), Mo is a necessary component of the enzymes involved [125,126]. Nitrogen metabolism is indirectly impacted by Mo shortage or supplementation [15].

Mo deficiency symptoms include chlorosis on leaves, stunted growth, and a necrotic appearance of the leaf tips [127]. Mo and N deficiencies have similar effects. Their deficit leads to the retardation of wheat growth, hence lowering the nutritive quality of the grain (Table 1) [128].

Mo application can contribute to an effective pretreatment for obtaining successful physiological growth parameters, metabolic progressions, and macro- and micro-nutrient efficiency, increasing plant growth and antioxidant tolerance in diverse ways, which may increase the nutritive value of wheat grains [129,130]. For instance, it increases antioxidant enzyme activities, abscisic acid (ABA) production, N assimilation, and Fe nutrition. The results of Moussa et al. [128] support the claim that molybdenum (Mo) application enhances the dry plant biomass, grain production, and distribution of micronutrients (copper (Cu), iron (Fe), manganese (Mn), zinc (Zn) (Table 1)). When Mo was applied to wheat organs, it increased the uptake of N, P, K, Cu, Fe, Mn, and Zn and significantly enhanced the growth and grain yield output of wheat cultivars that were either Mo-efficient or Mo-inefficient. This suggests that increased nutrient acquisition may boost the nutritional content of the grain yield [131]. An integrated approach to Mo application can achieve balanced nutrition and provide good-quality wheat grain in high yields [16,132]. Rana et al. [133] further stated that the application of Mo can supply the limited micro-nutrients found in foods and reduce the population affected by malnutrition due to a lack of these nutrients. Likewise, various researchers have shown that micro- and macro-nutrient fertilizer accumulation is directly affected by Mo deficiency [130,134]. Researchers claimed that seed treatment is more efficient for the application of Mo than soil application. In the study, 48 experiments were performed in eastern India, and the application of Mo raised the mean yield by 17–22%

compared to the control, and for the Mo soil application, the increase was 20–25% [135]. Similarly, Malla reported that molybdenum seed treatment (4 g kg^{-1} seed) was more efficient and cost-effective, boosting the yield by 15.79%, than a 1.5 kg/ha soil application, which had a yield increase of 10.53% [136].

The guiding effects of Mo on the N transformation process increase the wheat biomass and N uptake through a decrease in NO_3^- accumulation in the soil. This also significantly affects the root morphology and root exudates and, eventually, improves root growth [137,138]. Glutamine synthetase and nitrate reductase are a few examples of Mo- and P-related enzymes whose activity is enhanced by Mo application [131]. Mo also plays a significant role in N cycling in many ecosystems [139]. Mo has a crucial function in more than 60 enzymes that catalyze various redox processes; thus, compared to other micronutrients, it is an essential trace nutrient [140]. For xanthine oxidase, sulfite oxidase, and aldehyde oxidase to function, the coenzymes must contain molybdenum (Mo). Molybdenum deficiency in humans can cause lens displacement, convulsions, and intellectual impairment. In addition, a patient receiving complete, long-term parenteral feeding will develop sulfite toxicity due to Mo deficiency. In Siberia, Russia, and China, growing children with selenium deficiency may develop chronic osteoarthropathy (Kashin–Beck disease) [141]. There are several symptoms, including tachycardia, tachypnea, headache, nausea, vomiting, and coma [142]. Therefore, Mo inclusion in fertilizer formulation is necessary to increase the yield and mitigate most of the challenges faced by human populations related to the consumption of Mo-deficient foods. Nevertheless, there is a need for more research on the micro-nutrient contents and their allocation within wheat grains.

3.6. Manganese (Mn)

Manganese is one of the essential micronutrient fertilizers that should be available to plants in the right proportion, because it is a component of enzymes that perform tasks such as photosynthesis and lipid biosynthesis and protect cells against reactive oxygen species [143,144]. It is part of the essential antioxidant superoxide dismutase, which defends plant cells by lowering the level of free radicals that can harm plant tissue (Table 2). The Photosystem II water-splitting protein, which is necessary for photosynthesis, primarily comprises this nutrient. Furthermore, it serves as a stimulator of more than 35 enzymes and as an electron storage and delivery system for the chlorophyll reaction centers [145]. Mn is a member of hydroxylamine reductase, which carries out the reduction of hydroxylamine to ammonia, as well as an assimilation enzyme that reduces carbon dioxide during photosynthesis [146]. Mn is a crucial plant nutrient for plant and animal metabolism, while for humans, Mn is required for reproduction, carbohydrate and lipid metabolism, and neurological functions. Crops cultivated for food production are the essential food sources of Mn for humans [147,148].

It's common to confuse Mn deficiencies for Fe deficiencies in plants. However, Mn deficiency manifests as interveinal chlorosis (yellow leaves with green veins) of the young leaves, occasionally with tan, sunken blotches on the chlorotic areas between the veins, as well as plants with retarded growth and disproportionately small sizes (Figure 1) [149,150]. Mn insufficiency is a common issue in sandy soils, organic soils with a pH above 6, extensively weathered soils, calcareous soils, and soils with poor ventilation. Typically, Mn deficit is exacerbated by cold and wet weather [150,151]. Manganese deficiency results in a lower dry matter production and yield, thus weakening structural resilience against diseases and reducing tolerance to drought and heat stress [14,148]

According to a paper by Mudarisov et al. [152], manganese and zinc have considerable effects on the yield of wheat flour used in baking. Depending on the application technique, the precise concentration of microelements during the pre-sowing treatment and application in the growing season enhances the wheat yield unevenly. It was evident that the treatment of wheat seeds before sowing and the application of 0.1% solutions of manganese sulfate and zinc sulfate in the vegetative plant stages of tillering phase—the beginning of booting period—resulted in the highest yield of bread flour, corresponding to the first grade. Similarly, Ali et al. [153] reported that the wheat yield parameters, grain, and nutrient quality were significantly impacted by the application of manganese using different techniques (foliar and soil methods). Findings obtained by Shahrajabian et al. [154] showed that manganese sulfate fertilizer produced high values for the grain yield, harvest index, weight, protein, and manganese content in grains.

Research conducted by Liu et al. [155] proved that a lack of manganese decreased wheat grain production. The amount of recovered Mn ranged from 28.1% to 33.0%. Results obtained by Abbas et al. [156] indicated a sustainable and high crop yield due to the Mn supplied and the basal dose of NPK fertilizers. Using 12 kg Mn ha^{-1} proved to be the most cost-effective, providing the best net return, whereas Mn could be applied at 16 kg ha^{-1} to reach the maximum yield. The highest application of 16 kg Mn ha^{-1}, together with NPK, resulted in a grain yield of 4.59 t ha^{-1} compared to 3.96 t ha^{-1} resulting from NPK alone. Mn nutrition was investigated through conventional and no-tillage methods and significantly enhanced the yield, grain biofortification, and net benefits for CT and NT systems. Mn application through priming and foliar application may be an option for improving wheat production, profitability, and the grain Mn concentration. Under both tillage techniques, Mn foliar sprays produced the maximum grain Mn content (29% compared to no application). Osmopriming yielded the most significant financial return and marginal net advantages, according to the research [157].

Considering all these facts, the present review examined and acknowledged the essence of micronutrient fertilizers' inclusion in wheat production, since 30% of the individual daily calorie intake is obtained by consuming wheat worldwide [158]. Despite their importance, micronutrients can be toxic to wheat plants when the level of soluble nutrients in the soil exceeds the tolerance level. Of the micronutrients, boron and manganese, in terms of toxicity, are the most important for wheat production. Unlike nutrient deficiencies, there are few management or agronomic options for ameliorating toxicities. Boron toxicity symptoms are characterized by leaf necrosis and severe root stunting, and manganese toxicity symptoms include stunted growth, interveinal chlorosis, leaf tip necrosis, and brown spots on maturing leaves [96].

Excess Cu (Cu^{2+} above 1 µM) induces rhizotoxicity, with an overall reduction in root elongation, a significant decrease in the shoot Fe concentration, and the development of interveinal chlorosis symptoms, suggesting the induction of Fe deficiency, which has been identified an antagonist between Cu and Fe [159]. Indeed, in wheat, Cu and Mn phytotoxicity generally occurs in acidic or calcareous soils and in waterlogged or poorly drained soils [96,159]. Further studies are needed to determine the phytotoxicity of all microelements individually according to the soil type and their influences on each other during plant uptake using direct detection techniques.

4. Future Challenges and Research Directions

One of the main ways for farmers to increase wheat yields and their nutritional value is to use more micronutrient fertilizers. The effectiveness of micronutrient applications is influenced primarily by the source and form of the fertilizer, soil properties, application method, wheat characteristics and nutritional status, and climatic conditions. However, more research is needed to understand the interactions between these factors and the nutritional quality of the wheat.

The calculation of the correct micronutrient dose should be based on the field nutrient balance. The expected wheat yield determines the amount of nutrients that should be available. On the other hand, we need to carefully consider the available nutrients based on the soil testing and all the different nutrient inputs, such as the crop residues, organic inputs, atmospheric deposition, and nutrients in irrigation water, etc.

The nutrient requirements of a plant change during its development. In the wheat crop, there are three main "critical" periods when the greatest need for nutrients is observed: (1) budding—leaf feeding stimulates the growth of the main shoot, the establishment of side shoot buds in the axils of the germinating leaves, and the growth of the germ system; (2) tillering—the emergence of tillers activates morphophysiological processes, ensuring the growth of a secondary root system; and (3) the flag leaf stage, marking the beginning of the emergence of the ears—leaf treatment, in this stage, qualitatively improves the processes of flowering, grain formation, and development. Certain practices can be implemented to improve micronutrient availability at the right time. It is very important for farmers to understand that crop productivity is a stepwise process. Therefore if certain crop production aspects are not paid attention to in the early stages of development, agronomic practices in the later phases of plant development cannot compensate for the lag phase.

The effectiveness depends on the amount of necessary micronutrient fertilizer absorbed by the plant. In cases of deficiencies appearing during the growth cycle, it is important to act quickly and immediately in order to avoid any interruption of growth. To address these challenges, various strategies based on nanotechnology and genome-editing technologies seem promising, but very few studies have been conducted on these methods for wheat biofortification to date. Indeed, researchers should ensure that wheat receives an adequate supply of micronutrient fertilizers at the right time and in the right amount, and in-depth studies on the molecular mechanisms that regulate micronutrient uptake may help to solve this global problem.

Despite these potential benefits, the application of micronutrient fertilizers in wheat fertilization and stress management may be accompanied by risks to the environment, non-target plants, beneficial soil microbes, and other life forms that may be affected if the fertilizers are not used judiciously. Therefore, a better understanding of the agroecological consequences of micronutrient fertilizers, particularly in the context of dose–response analyses, interactions with macronutrient fertilizers, ion release, and specific effects of micronutrient particles on mineral nutrients, is essential for harnessing their full potential.

Since humans and animals are directly dependent on plants for food, nutrient deficiency in plants directly causes many health problems in humans and animals. In the meantime, it would be more efficient and less costly to provide the necessary micronutrients for improving the yield and chemical composition of wheat in order to solve the malnutrition problems of the growing population.

5. Conclusions

In this article, an effort was made to carefully review the past research results and their limitations, with particular emphasis on aspects of wheat response to micronutrient fertilizers. Many authors have concluded that the use of micronutrients mixed with macronutrients significantly increases plant growth, physiological traits, yield components, the yield, and most grain quality traits. Micronutrients also play a crucial role in animal growth and development. Subsequently, among the micronutrient fertilizer application techniques (seed dipping, soil applications), foliar application is promising in terms of its economic, agronomic, and ecological efficiency. Foliar-applied elements are relatively well absorbed when applied in a solution. A number of multifunctional formulations containing micronutrients in the required combinations should be developed more systematically and should cover larger crop areas.

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