Potential Challenges to Agronomic Biofortification

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Agronomic biofortification is the strategy to enhance the micronutrient contents in the edible parts of food crops through the application of mineral fertilizers. Agronomic biofortification can enrich crops with multiple elements, but the most common ones are Fe, Se, Zn, and I. It may be a suitable approach to reach resource-poor rural populations, provided they have access to chemical fertilizers. Soil-to-plant transfer and the accumulation of minerals in the edible portion of food crops determine the success of biofortification. In addition, the bioavailability of minerals from biofortified crops in the body influences the effectiveness of biofortification programs.

agronomic biofortification dietary intake effectiveness fertilizers

1. Mineral Fertilizer Manufacturing

One of the major challenges of agronomic biofortification as a strategy is the manufacturing of fertilizers containing a suitable quantity of mineral micronutrients, especially in many developing countries, where most fertilizer is imported. Strategies aiming to reduce MNDs are likely to be more effective where the intervention is case-sensitive in local situations [1][2]. To produce a fertilizer blend for a specific location is likely to require the close involvement of public and private fertilizer production and distribution sectors.

2. Mineral Fertilizer Application Method

There are two approaches for the application of mineral fertilizers—foliar and basal application. The two approaches have their costs and benefits in terms of logistics, economic feasibility, and final grain mineral concentration.

In the short term, foliar Zn applications are more effective than soil applications at increasing grain Zn concentrations in wheat [3][4]. For example, foliar Zn application to rice and wheat represents an effective agronomic practice to enhance the grain Zn concentration up to 66%, while soil application has no effect [3][5]. Soil applications of Zn are less effective than foliar applications to increase grain Zn concentration. The study by Joy et al. [6] indicated that soil Zn application led to increases in the median Zn concentrations in maize, rice, and wheat grains of 23%, 7%, and 19%, respectively, while foliar application led to increases of 30%, 25%, and 63%, respectively. The authors suggested that Zn fixation in the soil makes foliar applications more cost-effective than soil applications; however, the deployment might be more complicated. Botoman et al. [7] reported that many studies on soil Zn applications are underpowered to detect small increases in crop Zn concentration; they reported a 15% increase in maize Zn concentration as a result of 30 kg ha^{-1} elemental Zn application. A study from Zimbabwe aimed at quantifying the potential health benefits of alleviating dietary Zn deficiency with soil-applied Zn fertilizer and improved soil fertility management (ISFM) to increase maize grain Zn concentration reported that soil Zn fertilizers were estimated to increase the dietary Zn supply from 9.3 to 11.9 mg Zn $capita^{-1}$ day^{-1}, reduce the dietary Zn deficiency prevalence from 68% to 31%, and save 6576 DALYs lost per year. On the other hand, soil Zn fertilizer, together with ISFM, is estimated to increase the dietary Zn supply from 9.3 to 12.5 mg Zn $capita^{-1}$ day^{-1}, reduce the dietary Zn deficiency prevalence from 68 to 25%, and save 7606 DALYs lost per year [8]. Therefore, the report indicates strong effects of other ISFM approaches on the effectiveness of soil-applied Zn.

One benefit of soil application of Zn fertilizer is its potential residual effects in subsequent cropping seasons. For example, Narwal et al. [9] reported that soil application of Zn to wheat has a significant effect for multiple years and could be more effective and economical for wheat in the long run as compared to foliar application. Another study reported that soil application of 28 kg ha^{-1} $ZnSO_4$ fertilizer was an effective strategy to correct soil Zn deficiencies for about 7 years [10]. Similarly, Frye et al. [11] reported the residual effect ranging from 4 to 5 years as a result of soil application of 34 kg ha^{-1} $ZnSO_4$ fertilizer. Similar researchers reported that soil application of $ZnSO_4$ ranging from 18 to 28 kg h^{-1} is adequate to correct Zn deficiency in plants for four to seven years [12][13][14]. Therefore, the argument is, if the application of Zn fertilization is planned for more than one season, basal application could be a more cost-effective method due to its residual effect, whereas foliar application may provide the highest grain Zn concentration for a single production season.

Some studies have indicated that the combined application of soil and foliar Zn and Fe are more effective than a single soil or foliar application. The results indicate an increase from 25 to 100% grain mineral content due to combined soil and foliar fertilization application [3][5][15][16][17][18]. However, it is very crucial to consider the soil type effect since the combined foliar and basal application method of Zn on wheat is reported to highly depend on the soil type [4].

Ngigi et al. [19] suggested that foliar application of Se was more effective than soil application for maize and beans. However, it is important to consider that Se can act both as an antioxidant and a pro-oxidant, and in its concentrated form, Se is toxic [20], therefore, blended or granular Se applied to soils is the only safe approach for farmers. Ros et al. [21] argued that soil application of Se could result in similar responses to foliar-applied Se fertilizer, and the effects of soil-applied Se lasted longer than foliar-applied Se since residual effects were observed for up to 4 years. Chilimba et al. [22] also reported no significant difference between basal and foliar application of Se. They reported for each gram of Se ha^{-1} applied, the Se concentration in maize grain increased by 11–29 µg Se kg^{-1} and by 11–33 µg Se kg^{-1} for foliar and basal applications, respectively. The only comprehensive nationwide experience that has deployed Se fertilization with basal application, in Finland, reported a 15-fold increase in crop Se content [23].

Soil application of Fe usually has no or only limited residual effects, as Fe^{2+} is rapidly converted into Fe^{3+} in soils; therefore, foliar application has been considered the most effective method, especially for plants that develop grain months after germination [3][9][24][25]. However, other studies found that neither soil nor foliar application of Fe fertilization was an effective method to enhance wheat, barley, or oat Fe concentrations [26][27]. In contrast, regular foliar Fe application could result in a potential environmental hazard [28]. Manzeke-Kangara et al. [29] and Aciksoz et al. [26] argued that the efficiency of soil Fe application is more dependent on other factors, especially the integration of N fertilization and ISFM, compared to the Fe fertilizer application method (foliar or basal).

Studies have suggested the potential of a multi-mineral agronomic biofortification strategy to address multiple mineral deficiencies, based on a site-specific biofortification strategy. Mao et al. [2] reported that combined Se, Zn, and I fertilizers were as effective as singly-applied fertilizers when applied to maize, soybean, potato, and cabbage. This suggests that multi-mineral agronomic biofortification has the potential to address multiple MNDs simultaneously. However, knowledge about the elemental antagonistic and synergetic interaction effect is very critical. Pahlavan-Rad and Pessarakli, [24] reported 8% and 13% increases in wheat grain Fe and Zn concentrations, respectively, as a result of Fe and Zn interaction in their study on the combined application of Fe and Zn fertilization. Even though the mechanism of Zn and Fe interaction is not well understood [30], it has been reported that Zn treatment resulted in Fe accumulation in soybean roots and increased root-to-fruit Fe translocation in tomato plants [31].

3. Mineral Interaction Effect

Interactions between phosphorus (P) and Zn and between P and Fe in soils and plants have long been recognized and well documented. Studies have reported that high soil P levels can negatively affect Zn and Fe uptake by crops by inhibiting the mycorrhizal colonization of roots and resulting in impaired nutrient uptake [32][33]. Multiple studies have reported that P deficiency in soil results in a higher accumulation of Zn, whereas Zn deficiency in soil leads to a higher accumulation of P in plants [34][35][36]. Similarly, Fe deficiency stimulates the absorption of P in both roots and shoots [37][38][39][40]. Erdal [41] reported that soil Zn application enhances wheat grain Zn, and at the same time, significantly reduces grain P concentration. Another study also reported the association between Zn fertilization and a reduction in the phytic acid in rice grain, ranging from 14.8 to 30.4% [15]. These findings suggest that agronomic biofortification with Fe and Zn might also be a useful strategy to reduce antinutritional factors, such as phytate, in addition to increasing the grain mineral concentration.

A study that employed a factorial design involving the application of N up to 60 kg ha^{-1} and Zn up to 10 kg ha^{-1} on pearl millet indicated that the highest grain Zn concentration was observed at the application of 20 kg N ha^{-1} and 5 kg Zn ha^{-1} [42]. Similarly, the Zn uptake rate was enhanced by 4-fold due to the increased N application [43]. Similarly, multiple studies have indicated that N significantly enhances grain Zn [44][45] and Fe [26][29][46][47] concentrations. Nitrogen can increase the activity of transporter proteins and nitrogenous compounds, like nicotianamine, which helps to maintain Zn root uptake and shoot translocation [47][48], and by increasing the activity and abundance of Fe transporter proteins, such as yellow stripe 1 (YS1), in root cell membranes [49][50], which positively affects the root uptake and shoot transport of Fe. Similarly, the Se concentration of rice grains increased by 54.6% as a result of a combined Se and N application compared to only Se application as a fertilizer [51]. These findings suggest the application of Zn, Fe, and Se as a fertilizer is more effective when they are applied along with N fertilization and ISFM.

4. Environmental Impact

Uncontrolled and excessive mineral fertilizer use could cause contamination risk in the environment from the minerals of interest. It has been reported that about 28 tons of extra Cu per year is released into the soil in parts of the United Kingdom as a result of Cu fertilizer [52]. Furthermore, the long-term application of mineral fertilizer was reported to adversely affect important rhizospheric microorganisms that play major roles in plant nutrition and health [53][54][55]. In such cases, it is recommended to use nanoparticle fertilization, which potentially reduces the release of excessive mineral fertilizers into the environment. For instance, the application of Fe oxide nanoparticles on wheat [56], Zn oxide on maize [57], and Se nanoparticles on soybean [58] effectively improved grain Fe, Zn, and Se concentrations, respectively, without extra mineral release into the environment.

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