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Agronomic biofortification of crops to fight hidden hunger in sub-Saharan Africa

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ABSTRACT

Micronutrient deficiencies or ‘hidden hunger’ resulting from unbalanced diets based on starchy staple crops are prevalent among the population of sub-Saharan Africa. This review discusses the effectiveness of agronomic biofortification - the application of mineral micronutrient fertilizers to soils or plant leaves to increase micronutrient contents in edible parts of crops – and it's potential to fight hidden hunger. There is evidence that agronomic biofortification can increase yields and the nutritional quality of staple crops, but there is a lack of direct evidence that this leads to improved human health. Micronutrient fertilization is most effective in combination with NPK, organic fertilizers and improved crop varieties, highlighting the importance of integrated soil fertility management. Agronomic biofortification provides an immediate and effective route to enhancing micronutrient concentrations in edible crop products, although genetic biofortification may be more cost effective in the long run.

1. Introduction

Hidden hunger or micronutrient deficiency retards the growth and development of both crops and humans. Soil micronutrient deficiencies limit crop productivity and nutritional quality of foods, which together affect nutrition and human health (Sanchez and Swaminathan, 2005). Many soils in sub-Saharan Africa are affected by multiple nutrient deficiencies including the macronutrients N, P, K, secondary nutrients S, Ca and Mg, as well as the micronutrients Zn, Fe, Cu, Mn, Mo and B (Vanlauwe et al., 2015). Soil micronutrient deficiencies are thought to be severe in sub-Saharan Africa, where 75% of the total arable land has serious soil fertility problems (Toenniessen et al., 2008). Insufficient micronutrient availability in soils in these regions not only causes low crop productivity, but also poor nutritional quality of the crops and consequently contributes to malnutrition in the human population (Nubé and Voortman, 2011; Hurst et al., 2013; Kumssa et al., 2015). Diets in sub-Saharan Africa (especially among resource poor households) are often low in diversity and dominated by staple crops such as maize, rice, cassava, sorghum, millet, banana and sweet potato. Such diets are poor in micronutrients (minerals and vitamins) and consequently micronutrient deficiencies are widespread (FAO, 2015). The chronic lack of micronutrients can cause severe but often invisible health problems, especially among women and young children (Black et al., 2013): hence ‘hidden hunger’.

Worldwide over 2 billion people suffer from iron (Fe), zinc (Zn) and/or other (multiple) micronutrient deficiencies (WHO, 2016; Black, 2003). The problem is most severe in low- and middle income countries, especially in Africa where the estimated risk for micronutrient deficiencies is high for Ca (54% of the continental population), Zn (40%), Se (28%), I (19%) and Fe (5%) (Joy et al., 2014). In sub-Saharan Africa, micronutrient deficiencies are responsible of 1.5–12% of the total Disability Adjusted Life Years (DALYs)[1] (Muthayya et al., 2013). Alarming numbers concern iron deficiency anaemia, which affects more than half of the female population in countries such as DR Congo, Ghana, Mali, Senegal, Togo (IFPRI, 2015). Many people suffer from multiple micronutrient deficiencies (Muthayya et al., 2013); for example in Malawi > 50% of the households are estimated to be at risk of Ca, Zn and/or Se deficiencies (Joy et al., 2015a). Selenium is not essential for plant growth, but contributes to the human diet through uptake by crops from the soil. Even mild to moderate deficiencies of micronutrients can lead to severe human health problems, generally related to sub-optimal metabolic functioning, decreased immunity and consequently increased susceptibility to infections, growth failure, cognitive impairment and, finally, reduced productivity (Tulchinsky,

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[1] DALYs are the sum of Years of Life Lost (YLL) and Years Lived with Disabilities (YLD) for people living with a disease or consequential health condition. One DALY can be thought of as one lost year of ‘healthy’ life. The sum of these DALYs across the population, or the burden of disease, can be thought as a measurement of the gap between current health status and an ideal health situation where the entire population lives to an advanced age, free of disease and disability (www.who.int/healthinfo/global_burden_disease/metrics_daly/).

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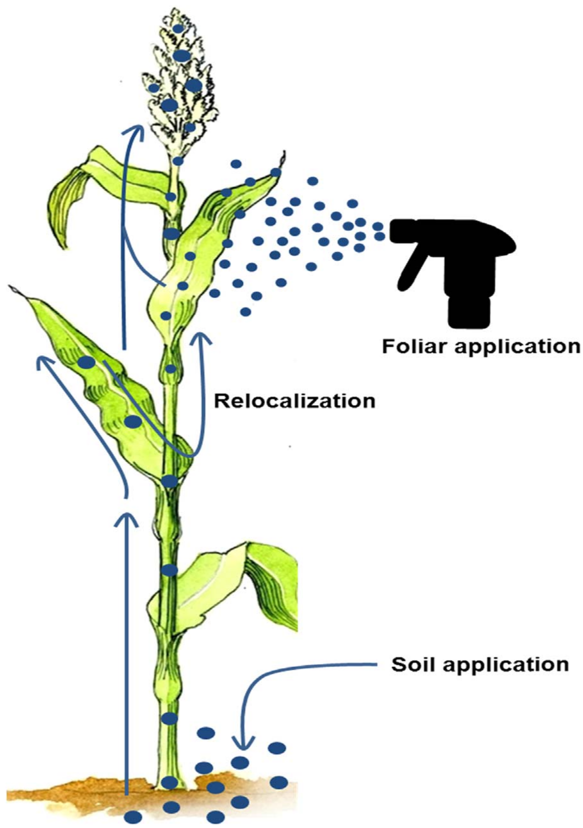

Fig. 1. Agronomic biofortification is the application of micronutrient-containing mineral fertilizer (blue circles) to the soil and/or plant leaves (foliar), to increase micronutrient contents of the edible part of food crops. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2010).

Hidden hunger can be alleviated by direct (nutrition-specific) and indirect (nutrition-sensitive) interventions (Ruel et al., 2013). Direct interventions focus on consumption behaviour and include dietary diversification, micronutrient supplementation, modification of food choices and fortification. Nutrition-sensitive interventions address the underlying determinants of malnutrition and include biofortification. Biofortification is the process of increasing the content and/or bioavailability of essential nutrients in crops during plant growth through genetic and agronomic pathways (Bouis et al., 2011). Genetic biofortification involves either genetic engineering or classical breeding (Saltzman et al., 2013). Agronomic biofortification is achieved through micronutrient fertilizer application to the soil and/or foliar application directly to the leaves of the crop (Fig. 1). Biofortification is mainly focused on starchy staple crops (rice, wheat, maize, sorghum, millet, sweet potato and legumes), because they dominate diets worldwide – especially among groups vulnerable to micronutrient deficiencies - and provide a feasible means of reaching malnourished populations with limited access to diverse diets, supplements, and commercially fortified foods (Saltzman et al., 2013).

We review evidence on the effectiveness of agronomic biofortification and its potential to alleviate hidden hunger in sub-Saharan Africa. First we discuss some technical aspects of agronomic biofortification concerning micronutrient bioavailability pathways and micronutrient fertilization approaches. We then address the questions: (1) what is the impact of agronomic biofortification on a) yields and nutritional quality of crops, b) nutrition and human health status, c) the environment, and 2) how effective is agronomic biofortification compared with other interventions? We focus on agronomic biofortification with Zn, Se and Fe, as these micronutrients are considered to be the most appropriate for the technique and are highly important for human health (Cakmak, 2014; Welch and Graham, 1999). We conclude with an analysis of the potentials and constraints for implementation of agronomic biofortification in sub-Saharan Africa).

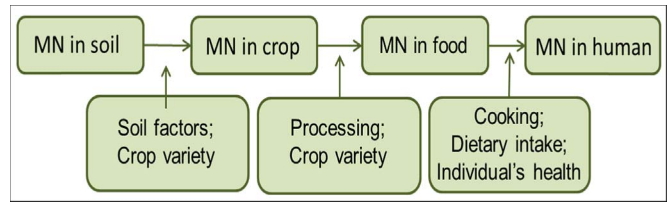

Fig. 2. Schematic overview of micronutrient (MN) pathway from soil to humans and the factors that influence MN bioavailability to the next level. Based on Mayer et al. (2011).

2. Micronutrient bioavailability

Micronutrients follow a path from the soil through the crop and food into the human body. Several critical factors determine the success of agronomic biofortification to alleviate micronutrient deficiencies among humans. These factors depend on nutrient bioavailability at different stages: the presence and bioavailability of soil nutrients for plant uptake (soil to crop), nutrient allocation within the plant and re-translocation into the harvested food (crop to food), bioavailability of nutrients in prepared food for humans and the physiological state of the human body which determines the ability to absorb and utilize the nutrients (food to human) (Fig. 2).

2.1. Soil to crop

Bioavailability of micronutrients from soil to crop is influenced by many soil factors (i.e. pH, organic matter content, soil aeration and moisture and interactions with other elements) and by the crop variety that, for example, defines the structure and functioning of rooting systems (Alloway, 2009). Some plants can modify the rhizosphere by the excretion of H^+ ions or organic acids that enhance micronutrient availability and uptake (Zhang et al., 2010; Marschner, 2012). Interactions between elements influence the bioavailability for root uptake. Soil phosphorus, for example, can either stimulate root growth and Zn uptake while at the same application of P fertilizer can precipitate already small concentrations of Zn and trigger Zn deficiency (Zingore et al., 2008). Addition of P also appears to induce Zn deficiency through dilution effects and interference with Zn translocation from the roots (Singh et al., 1988). Soil management with lime or organic manures can alter soil properties such as pH and stimulate micronutrient bioavailability and crop uptake. Symbioses with arbuscular mycorrhizal fungi (a fungal network acting as an extension of the root system and increasing the volume of soil explored for nutrient uptake) can increase uptake of nutrients that are sparingly soluble in soil, such as P and Zn (Smith and Read, 1997).

2.2. Crop to food

Bioavailability from crop to food is influenced by the crop (variety) – which defines whether micronutrients are (re-)localized into edible parts of the crop – and by food processing. In rice, Zn and Fe are localized in protein bodies in the outer layer of the grains, which is often removed during processing (dehusking, milling) leaving less Zn and Fe in the consumed rice (Haas et al., 2005; Zimmermann and Hurrell, 2007). Rice parboiling is an effective method to increase nutrient contents especially when micronutrients are added to the soak water during the parboiling, as the process drives nutrients from the bran and germ layer to the endosperm (Prakash et al., 2016; Hotz et al., 2015). Other crops like wheat allocate Zn in the consumed part of the grain (endosperm) that remains even after removal of the seed coat and aleurone layer during the process of bread making (Ajiboye et al.,