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REVIEW

Unlocking the multiple public good services from balanced fertilizers

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Abstract
Fertilizers produce over half of the world's food and permit less encroachment into pristine lands. Yet, the low uptake efficiency by crop plants causes nutrient losses that drive global change. Mitigating measures have been insufficient to address the problems, and policy interventions, NGO involvement, and R&D investments have been too insignificant to transform the fertilizer sector. Here, we discuss the contribution of balanced mineral fertilizers to increasing the nutritional value of crop produce to improve human nutrition and health; healthier plants to reduce biocide use; plant robustness to enhance tolerance to abiotic stresses; and increased metabolite production to improve taste and shelf-life. We reflect on raising awareness about these multiple fertilizer-based public good services for realizing several Sustainable Development Goals which can be achieved through a comprehensive nutrient assessment to catalyze transformation in research, policy and industry.

Keywords Micronutrients · Plant health · Human health · Food loss · Resilience · Innovative fertilizers · Sector transformation

1 Background

Global food demand is expected to increase by 70% in 2050, due to a rise in population growth, along with improving incomes and associated dietary changes. This projection reaches 100%–170% for developing countries (Alexandratos and Bruinsma 2012), where close to 800 million people are food-insecure and hidden hunger affects two billion people, with micronutrient and vitamin deficiencies contributing significantly to high mortality rates (McClafferty and Zuckermann 2015). The path of agricultural intensification through advanced technologies, principally high-yielding crop varieties, irrigation development, mechanization and energy use, and agronomic inputs including fertilizers and biocides, prevented larger-scale famine in the past. The use of mineral fertilizers, especially nitrogen (N), phosphorus (P) and potassium (K), has been at the core of agricultural productivity increase, with synthetic N contributing to roughly half of the world's food production (Erisman et al. 2008). Fertilizers also have been useful for increasing biomass production to be incorporated into soils to sequester carbon. Furthermore, fertilizer use has increased crop yields, which contributed to curtailing encroachment into natural lands (Gibbs et al. 2010), and with that, to saving almost a billion hectares of biodiverse ecosystems since the 1950s.

However, fertilizers also have caused significant ecological damage. The global landscape of fertilizer-related issues can be broadly categorized into two. First is the need to reduce losses from mineral fertilizers, while maintaining or increasing crop yield. This is the situation in Northern America, Europe, and South and East Asia (Bouwman et al. 2017). Second is the need to increase the use of balanced mineral fertilizers on soils with low and unbalanced nutrient availability, as is the case in sub-Saharan Africa, where green and animal manures are insufficient to sustain soil health, and where continuous cropping with insufficient nutrient replenishment leads to the depletion of over 50 kg ha^{-1} $year^{-1}$ of N, P and K combined (e.g. Lesschen et al. 2007; Cobo et al. 2010). This estimate does not account for secondary elements and micronutrients.

Nitrogen and phosphorus fertilizers, collectively, have been identified among the nine major drivers of global change (Rockström et al. 2009). Fertilizers, directly and indirectly, affect other drivers as well, including climate change, ozone depletion, ocean acidification, land use, water quality and

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biodiversity (Angle et al. 2017). The effects of N and P losses can, for instance, be seen in the pollution of waterbodies, including eutrophication and dead coastal zones like the Chesapeake Bay and the Great Barrier Reef. Most prominent is the impact of N, of which total global loss from agricultural production should not exceed 50–100 Mt. N y^{-1} to remain within the safe operating space of the planetary boundaries (Steffen et al. 2015). Whereas Zhang et al. (2015) estimate that the overall global N use efficiency must increase from the current 0.4 to 0.7 (Nyield/Ninput) to limit N losses to 50 Mt. y^{-1}, Conijn et al. (2018) estimate that even a comprehensive set of agronomic and dietary measures by 2050 would not push back the N losses to within the safe operating space.

These unintended side effects of fertilizers have led, for instance, to policy regulations in Europe in the 1980s to limit losses (Bindraban 2012) and also to a cap on the use of fertilizers by 2020 in China (Heffer and Prud'homme 2015). The fertilizer industry, particularly in North America, promotes 4R Nutrient Stewardship, i.e. the application of the right fertilizer, at the right amount, right time and right place (IPNI 2014) to increase the uptake efficiency of fertilizer nutrients and reduce losses. As an example in this regard, the International Fertilizer Development Center (IFDC), helped to develop the urea deep placement technology (UDP) several decades ago (Savant and Stangel 1990), i.e. compressing prilled urea kernels into urea super granules of 1 cm diameter weighing about 1.2 g that are individually paced at 7–10 cm below the soil surface in the center of 4 rice plants 1–7 days after transplanting. Following adjustments to local conditions for Bangladesh, primarily in mechanization of application, the technology has been adopted by an estimated two million farmers and has recently been demonstrated to contribute significantly in reducing N application rates, in increasing N uptake efficiency, and in reducing N losses as volatilized ammonia or emitted N-oxides, especially in lowland rice production systems (Gaihre et al. 2015; Angle et al. 2017). Furthermore, a derived technology, fertilizer deep placement (FDP), is being expanded for adoption as a broader fertilizer management strategy in many Sub Saharan African countries, following its successes in Bangladesh (IFDC 2017). Numerous studies in Africa confirm the need for balancing fertilizer nutrients to obtain highest yield responses and uptake efficiency (e.g. Kihara and Njoroge 2013). In Europe, recapturing of nutrients from air, water, waste and offal is being promoted, as included in policies for the development of a circular economy (Haas et al. 2015).

However, while these agronomic measures to mitigate losses may have improved the situation in specific geographical areas, they have globally been insufficient to curtail fertilizer-related problems as evident from the planetary boundary assessments, and have not yet led to drastic policy interventions. This is in addition to the dismal investments in fertilizer R&D by the industry, wherein Fuglie et al. (2011) estimate that the fertilizer industry invests only 0.1–0.2% of its revenue in R&D, compared with about 10 and 15–20% by the seed and pharmaceutical sectors, respectively. Public concern, however, results in an ever-louder call from society for less-intensive production systems, like disallowing the use of chemicals, including mineral fertilizers in organic agriculture (Bedoussac et al. 2015). Nevertheless, crop productivity under natural conditions, without use of mineral fertilizers, remains at maximum levels of 2–2.5 t ha^{-1} grain equivalents, given the limited availability of nutrients (WRR 1995). These levels are recorded from the most advanced ancient civilizations such as China and Latin America, for pre-green revolution wetland rice cultivation (Bindraban et al. 2006) and around 1900 in Europe and can sustain food volumes for no more than 2–3 billion people. Indeed, there is an expanding body of literature that shows fertilizers to be an essential component for sustained yield increase in cropping systems and to be very profitable in much of Sub Saharan Africa (e.g., Droppelmann et al. 2017; Jama et al. 2017). Moreover, it is not likely that overall nutrient losses from organic sources would be much less than from mineral fertilizers (Lorenz and Lal 2016; Angle et al. 2017).

Hence, the current dialogue on fertilizers has not triggered policymakers to put firm policies in place for the transformation of the fertilizer sector. It has not propelled NGOs to develop a balanced and unifying strategy to advocate for dramatic changes, nor for the industry to make significant investments. Yet, all these are needed to ensure global food security, while reducing the negative side-effects of fertilizers within the limits of our planetary boundaries. It is from this view that Bindraban et al. (2015) reflected on current fertilizers and called for a paradigm shift on fertilizer "design," "packaging" and "delivery" of nutrients to plants by a more deliberate adoption of knowledge of plant physiological processes, rather than mainly chemistry, as an entry point. This approach would align nutrient supply to plant demand, and feed the plant rather than the soil. Dimkpa and Bindraban (2016) elaborated on these basic principles, and argued for heightened emphasis on secondary and micronutrient-containing NPK fertilizers, also referred to here as "balanced fertilizers."

In this paper, we expand these arguments, and present evidence for a broad spectrum of additional plant-based benefits that can be attained from systems-specific and judicious adoption of balanced fertilization. We present evidence for balanced mineral fertilizers contributing to increased nutritional value of plant produce that can improve human nutrition and health; to healthier plants that could reduce the need for pesticides and herbicides; to plant robustness that enhances tolerance to drought; and to increased production of metabolites that improves taste and shelf-life. Subsequently, we reflect on the need to raise awareness, likely through a comprehensive nutrient assessment, about these multiple public good services that fertilizers can deliver, thereby contributing to realizing several Sustainable Development Goals (SDGs), which can catalyze the needed transformation in policy, civil society, research and industry.

2 Fertilizers in plant and human nutrition

Increasing the genetic yield potential, and the actual yield of cereal crops through optimized agronomic practices, over the past six decades has been a formidable achievement that improved world food security. At the core of such agronomic practices is increased use of macronutrient fertilizers composed of NPK. At the same time, however, use of micronutrient- containing fertilizers has not similarly advanced, globally. Concomitant with increased use of NPK is the introduction and adoption of high-yielding crop varieties that require high rates of N to meet their yield potentials. Under these conditions, the concentration of micronutrients in grains of cereal crops and in shoots of vegetables have declined, sometimes by more than half (Davis et al. 2004; Fan et al. 2008; Garvin et al. 2006; Graham et al. 2007; Mayer 1997; White and Broadley 2005). This decline may be attributed to the dilution of micronutrients in shoot and grain biomasses due to breeding (Monasterio and Graham 2000; Bänziger and Long 2000), and the continuous mining of soil micronutrients because of non-replenishment by fertilization, especially in resource-poor countries (e.g. Jones et al. 2013; Shukla et al. 2015).

The global burden of human malnutrition, arising from insufficient intake of secondary and micro elements like Ca, I, Fe, Zn, and Se, and metabolites like Vitamins A and C, is estimated to cost about US$35 trillion by 2030 (Bereuter and Glickman 2015), due to a decline in global human productivity arising from stunting, loss of cognitive skills, and other chronic illnesses. Strategies to address human malnutrition include diversity of diets, nutritional supplementation, fortification of processed food, and biofortification through breeding of crops with higher contents of micronutrients (Stein 2010). The effectiveness of each intervention varies dependent on the conditions and circumstances of the target group. Here, we propose to complement these strategies through agronomic fortification: i.e., the application of mineral micronutrient fertilizers to soil or plant leaves to increase micronutrient contents of edible plant parts. There is ample evidence that the application of micronutrients increases yield and/or nutrient contents above the levels obtained when NPK alone is added, certainly so in soils not responsive to NPK (Kihara et al. 2017; Vanlauwe et al. 2015). Accordingly, Dimkpa and Bindraban (2016) presented evidence of increases in micronutrient contents in edible parts of several crops from fertilization, on which basis more emphasis on agronomic fortification was argued, firstly, to revive and increase crop micronutrient contents, and, secondly, to utilize this option to improve human nutrition, down the line. Use of Zn-containing NPK fertilizers in crops such as wheat, rice, sorghum, and soybean, at specific timings and application routes, has, for instance, resulted in dramatic improvements in crop yield and nutritional quality (Cakmak 2008; Cakmak et al. 2010; Phattarakul et al. 2012; Zou et al. 2012; Dimkpa et al. 2017a, b). In their comprehensive review and modelling study, Joy et al. (2015) found soil and foliar applied Zn to increase median Zn concentration in maize, rice and wheat grains by 23, 7 and 19%, and 30, 25 and 63%, respectively. They estimated that using micronutrient-containing fertilizers could reduce disability-adjusted life years (DALYs) lost due to Zn deficiency by around 10%, depending on their modelled scenarios, in ten Sub Saharan African countries. Similar findings of significant and cost-effective interventions of Zn on DALY has also been reported for Pakistan (Joy et al. 2017) and China (Wang et al. 2016). In their review, De Valença et al. (2017) also show that agronomic fortification increases the content of several micronutrients, but argue that there is a lack of evidence that this leads to improved human health. Identifying such direct relationships will be difficult when diets are composed from complex food chains, but easier where food is produced and consumed locally (Akeredolu et al. 2011). In any case, humans must obtain several of their essential micronutrients from plants; therefore, there must be a link among soil, food, and under-nutrition (Oliver and Gregory 2015). In line with these authors, we argue for multidisciplinary research that includes soil and plant sciences, human nutrition, epidemiology, and medical sciences, to explore the relationship between agronomic fortification and human nutrition, which should be rooted in a sound understanding of the biological aspects of nutrient metabolism by plants.

3 Fertilizers in plant nutrition and human health

While there is a recent surge in papers linking agriculture, nutrition and human health through multidisciplinary research because of the growing attention to nutrition-sensitive agriculture (e.g., McDermott et al. 2015), few papers explicitly address agronomic fortification. And although the relationship between plant nutrition and human health appears distant, circumstantial evidence indicates a promising role of plant nutrition in human health. The role played in this regard by essential nutrient elements such as calcium (Ca), iron (Fe), and zinc (Zn), among others, is documented in the literature (see for example, White and Brown 2010; Oliver and Gregory 2015). Here, we provide additional insights on the role of other elements like selenium (Se) and silicon (Si) (Marafon and Endres 2013). These elements are regarded as non-essential for plant growth, as their deficiency does not interrupt the plant's life cycle. However, they do enhance growth and confer other benefits to plants.

In a recent review, Ros et al. (2016) noted agronomic fortification to be highly effective for increasing Se content in plant and dairy products through feeding by cattle, ultimately increasing human uptake. Along this line, the Finnish government mandated Se fortification in fertilizers, which increased Se levels of 125 indigenous food items including wheat, meat and dairy products, with human intake increasing from 25 μg day^{-1} in 1975 to 124 μg day^{-1} in 1989 (Eurola et al. 1991). Similar results of crop and soil fertilization with Se with dramatic impacts on animal and/or human Se intake have been reported for Australia, New Zealand and France. Compared to direct Se supplementation to food, agronomic Se fortification is advantageous in that (i) inorganic Se is assimilated into organic forms which are more bioavailable to humans, and (ii) plants act as an effective buffer against accidental excessive Se intake (Hartikainen 2005). Nevertheless, the direct impact on human health is difficult to assess, because the nationwide intervention in Finland does not allow a placebo-controlled comparison within the country. The incidence and mortality in cardiovascular diseases and cancers as endpoints that could have been affected by the increased Se intake appear to be more strongly determined by medical and life-style factors (Alfthan et al. 2015). Vinceti et al. (2015), however, suggest that epidemiologic investigations relating Se to human health should consider specific individual chemical forms of the metalloid, rather than overall Se content because of greatly differing toxic and nutritional properties.

Similarly, Si is also considered non-essential for plants and humans, but there is growing evidence for its significant impact on human health (Martin 2013), such as the potential to reduce osteoporosis (Rodella et al. 2014). Silicon modulates physiological and metabolic responses in both plant and human biology; evidence of the significance of silica nutrition for human health has mainly been contributed by plant-based foods. While the earth's crust contains large amounts of Si, only monosilicic acid ($Si(OH)_4$) is available to plants, but it is highly unstable and precipitates with heavy metals, leading to deficiencies. Laane (2016) reports significant yield responses, increased contents of other nutrients, and increased tolerance to biotic and abiotic stresses in several crops under field conditions, upon foliar application of stabilized non-colloidal silicic acid (produced through a patented process that prevents polymerization) in combination with other nutrients. Through controlled treatments, the author argues that the sole impact of Si could be demonstrated, and that the increased nutrient uptake could be explained by the catalytic impact of Si on enhanced root growth. The foliar substance comprising other nutrients might suggest synergistic effects among nutrients. Some of these findings are also reported by Farooq and Dietz (2015; and references herein). Si mitigates both toxicity and deficiency of phosphorus and heavy metals, including aluminum (Al), arsenic (As), cadmium (Cd), iron (Fe), manganese (Mn), and Zn, in plants by complexation and precipitation in the rhizosphere, apoplast and/or cell wall, which dissolves under deficiency to supply the relevant nutrient. Silicon also alleviates biotic stress through the production of anti-bacterial and anti-fungal compounds, deposition of silica near lesions, and overall strengthening of the cell wall (Cherif et al. 1994). The latter mechanism also helps to prevent lodging, reduce transpiration, which enhances drought tolerance, and maintain leaf erectness, which facilitates light interception. In humans, Si is necessary for the biosynthesis of collagen and glycosaminoglycans, which are required for organic bone matrix formation that strengthens bones and connective tissues. Si, through intermediary processes, prevents the occurrence of neurodegeneration in the brain, which reduces the risk of Alzheimer's disease. Farooq and Dietz (2015), therefore, suggest that Si-biofortification of crop plants can significantly affect silica nutrition for human health.

4 Fertilizers in plant health and resistance to disease and weed

Micronutrients are critical in the defense of crops against disease. Infections induce a cascade of reactions that result in the production of secondary metabolites that suppress progression of the infection. Enzymes required to generate these metabolites are activated by micronutrient cofactors. For example, Mn, Cu, and Zn enhance disease resistance by activating the host defense enzymes. Kaur et al. (2016) expanded on the impact of non-essential micronutrients for plants in resisting biotic stress, by triggering activation of genes to synthesize compounds that inactivate the pathogen. The speed with which plants respond to infections could depend, among other factors, on the micronutrient content in tissues. Servin et al. (2015) provide an overview of the impact of several essential and non-essential micronutrients in plant resistance to biotic stress. These authors focused on the role of nanoparticle micronutrient fertilization in specific diseases and, where known, provided the functional mechanisms involved. However, regardless of the form in which they are presented to plants, micronutrients act either systemically to trigger the activation of genes for the synthesis of anti-pathogenic compounds, or by directly inactivating the pathogen in the plant's environment.

Whereas broadcast application of fertilizers generally enhances weed infestation, they can be effective in controlling specific weeds as well. Innovation in crop fertilization can support the control of parasitic weeds such as striga (*Striga hermonthica*). Striga infestation dramatically reduces crop yield; its incidence is more pronounced under poor soil fertility. However, in infertile soils, plants such as maize, rice and other cereals, produce exudates, namely strigolactones, to stimulate the symbiotic relationship with arbuscular mycorrhizal fungi which assists the plant to scavenge the soil and overcome nutrient deficiency. Coincidentally, strigolactones also induce germination of striga seeds, of which, subsequently, the emerging striga plant parasitizes the host plant and competes for nutrients. Jamil et al. (2012, and several subsequent studies) showed that N and P fertilization and seed priming with P has significant impacts in reducing striga infestation in greenhouse experiments, albeit with less consistent results under field conditions. The lowered effectiveness in the field setting was ascribed to complex edaphic processes related to nutrient availability, climatic conditions, and plant responses. Notably, micronutrient fertilization could suppress striga infestation, given that specific micronutrients can enhance the bioavailability of N or P to cereal crops (Rietra et al. 2017; Dimkpa et al. 2017a, b) under a variety of conditions. For example, under drought stress, where strigolactone production is stimulated (López-Ráez 2015), micronutrient application, which enhances N uptake (Dimkpa et al. 2017a), may also help the plant to optimize nutrient use. Also, because striga biosynthesis involves carotenoids as precursors, and micronutrients inhibit carotenoids production (Pandey et al. 2009), they could potentially also reduce striga infestation.

5 Fertilizers in plant tolerance to drought

Drought affects nutrient bioavailability and uptake, resulting in low yields and nutritionally compromised produce quality. Drought is addressed through integrated soil-water management practices, along with the introduction of drought-tolerant crop varieties, such as for maize (Kamara et al. 2003). Yet, the ability of micronutrients such as Zn, Cu or B, as well as specific non-essential elements, in positively influencing crop response to drought stress through affecting root growth, the production of reactive oxygen species (ROS) that damage cells during abiotic stresses, and through cell wall strengthening, is notable (Dimkpa and Bindraban 2016). Silicon is involved in drought tolerance in grain crops by reducing leaf transpiration and water flow rate in the xylem vessel (Gao et al. 2004), facilitating water uptake and transport under drought conditions (Sonobe et al. 2010), and regulating the activities of antioxidant enzymes under drought stress (Ahmad and Haddad 2011). Kaur et al. (2016) presents an overview of non-essential nutrients in enhancing drought tolerance as well.

Dimkpa et al. (2017a) demonstrated the impact of micronutrient fertilization on water-deprived soybean, which, despite the application of NPK, suffered at maturity from drought stress, relative to watered plants: with 27%, 54% and 43% decreases in growth, grain yield, and shoot N uptake, respectively. However, with application either of soil or foliar micronutrient formulations composed of Zn, Cu and B, as a salt solution or nanoparticle suspension, the growth reduction caused by drought was virtually eliminated; biomass reduction was less by 27%; and loss in grain yield was lowered by 36%. Similarly, about 36%, 28%, and 45% more N, K, and Zn, respectively, were recovered in the shoot from the dry soil by the crop due to soil application of the micronutrient formulation. Notably, drought lowered grain Zn concentration by 24%, but this loss was virtually negated by Zn fertilization under drought. Thus, the nutritional quality of the edible produce can be improved under harsh environmental conditions with micronutrient fertilization. Similar findings have also been reported for other crops, including wheat and rice (Ashraf et al. 2014; Bagci et al. 2007; Movahhedy-Dehnavy et al. 2009), upon Zn treatment under drought.

Therefore, given that drought effects can be mitigated by incorporating Zn, B, Cu, and/or Si into fertilizer regimes in drought-prone agro-ecosystems, we argue for the integration of these nutrients in fertilizer recommendations, certainly so in crop varieties with enhanced drought tolerance, in order to maximize the expression of the crops' yield potential. This also implies a strategic integration of micronutrient fertilization in soil-water management practices for drought-tolerant crops to sustain productivity, and possibly improve the nutritional quality of produce under increasing water limitation. Moreover, because fertilizer supply via soil can be less efficient in availing nutrients in drying soils, we envisage that an interplay of soil-applied fertilizers based on geo-spatial exploration of soil-plant relations (Kempen et al. 2015), complemented with foliar application of micronutrients, in particular, one or all of Zn, Cu, B and Si, can enhance the drought tolerance of improved crop varieties. Optimizing nutrient blends for soil application, whenever necessary combined with foliar fertilization, may yield results in the immediate term given the current evidence from on-farm trials (Vanlauwe et al. 2015).

6 Fertilizers and plant post-harvest losses

Roughly one-third of food crop produce (almost 1.3 billion tonnes) is discarded, resulting in losses and waste (Gustavsson et al. 2011). Such wastage is associated with water, land and fertilizer losses, ranging from about 20 to 30% for different continents (Shafiee-Jood and Cai 2016). However, even greater losses might occur due to rapid urbanization, globalization, and climate change, suggesting that several integrated approaches and actions are needed to reduce food waste. In this regard, appropriate fertilization could contribute to reducing losses through impacting post-harvest produce quality. For example, calcium (Ca) increases cell wall stability and membrane integrity, and, therefore, firmness (Bing 2011). Leaky membranes due to Ca deficiency accelerates senescence, resulting in crop produce of lesser quality (integrity), and hence, in post-harvest losses. In potato tubers, Ca deficiency causes physiological disorders such as internal brown spot, hollow heart, and bruising. Because Ca moves with water in the xylem and less water moves to fruit and tuber tissues compared to leaves; and because Ca is less mobile in phloem (Karley and White 2009), Ca deficiency may easily occur in potato tubers, causing skin disorders (Palta 2010). Accordingly, the application of Ca during tuber bulking when roots arising from stolons and tubers supply Ca to tubers have been reported to reduce physiological skin disorder, in turn elongating shelf life (Ginzberg et al. 2012).

Similarly, boron plays a role in the synthesis and connection of hemicelluloses and other related cell wall materials involved in improving cell wall structure (Bing 2011; Cakmak and Römheld 1997). Moreover, B is involved in several enzymatic and metabolic processes, including translocation of sucrose by enhancement of a sucrose transporter (Shi et al. 2012); regulation of rubisco enzymatic processes (Bing 2011); and increasing ascorbic acid content (Molassiotis et al. 2006), which inhibits Reactive Oxygen Species (ROS). Boron deficiency lowers carbohydrate content, thereby affecting firmness and reducing fruit quality. Accordingly, a foliar application of B on tomato plants improved epidermal integrity and reduced susceptibility to cracking (Huang and Snapp 2009), and in watermelon, resulted in accumulation of sucrose (Li et al. 2010). Application of B on carrots increased Vitamin C content, inhibiting ROS production and preventing cellular damage (Gill and Tuteja 2010). In preliminary studies (Kendristakis 2017), cucumber fruits dipped twice in solutions of Ca, B and their combination showed enhanced firmness and greenness. This prolonged fruit shelf-life and increased carbohydrate content; the latter being an attribute for tastiness (Breslin 2013). Therefore, the inclusion of Ca and B, and likely other micronutrients, in fertilizer regimes could be strategic for improving produce quality, thereby reducing post-harvest losses.

7 Novel products and fertilization technologies to unlock fertilizer benefits

With the application of blended fertilizer granules, the benefits of micronutrient-containing fertilizers can already be unlocked. The application of 1–3 kg ha^{-1} or more of specific micronutrients can increase yield (Vanlauwe et al. 2015), as can for instance be observed through nutrient omission that elucidates the relative influence of each nutrient under specific crop and agroecological situations (Nziguheba et al. 2009), but the crop uptake of micronutrients is typically less than 5–10% (Baligar et al. 2001), and even less so for grain translocation. Because segregation of fertilizer blends can hamper homogenous distribution in fields, uptake efficiency might be increased by coating N or NPK fertilizer granules with micronutrients. This strategy has been observed to increase yields at least equally with less than half the amounts of micronutrients in preliminary maize trials (IFDC, unpublished data). Over time, innovative fertilizer products and alternative delivery mechanisms to plants should be developed and deployed to achieve improved agronomic, nutritional, and ecological outcomes. However, unlocking the spectrum of fertilizer benefits calls for aligning chemical, edaphic, and plant physiological processes. The occurrence of antagonism or synergism among the 14+ plant nutrients during uptake and growth (Rietra et al. 2017) ought to be considered in fertilizer formulations. That way, mutually compatible nutrients can be leveraged, while antagonistic ones are avoided during fertilizer formulation. Also, most nutrient-limiting phenomena such as antagonism among nutrients, extreme pH, and other complex chemistries occur mainly in the soil, as compared to the plant. This problem can be alleviated, at least partly, by complementing soil applications with foliar application, and possibly by injection or infusion of nutrients.

It has been noted that many of the nutrient transport proteins are active in both root and shoot. As such, specific micronutrients can be administered to the plant via the soil or leaves, dependent on which organ uptake would be better facilitated. However, systematic views about the effectiveness of foliar fertilizers remains rather haphazard (Voogt et al. 2013), due to the numerous environmental, edaphic and plant conditions affecting effectiveness (Noack et al. 2011), and despite systematic insights about uptake mechanisms (Fernandez and Eichert 2009). Yet, these and novel insights in biological uptake mechanisms along with ecological processes could be exploited to govern aerial uptake. Some plants, such as epiphytes (e.g., *Bromelia tillandsia*), have few roots and obtain nutrients mainly through their leaves (Benzing et al. 1976), like aquatic plants. Though this phenomenon is not found under production situations of *Bromelia* (Sonneveld and Voogt 2009), epiphytes appear to use their roots when they can and the foliar route when they must. This however suggests that there might be unbeaten paths that could guide breeders in exploiting genetic variations in this regard, and in modifying plant anatomical and morphological traits to enhance nutrient uptake.

One notable recent development with promise for application in fertilizer advancement is the growing knowledge that certain nutrients can be taken up by plants as intact particles, through a variety of uptake mechanisms, including endocytosis, aquaporin transport, ion channels, plamodesmata transport, stomata, or entry facilitated by organic matter, including root exudates (Schwab et al. 2016). Nutrient packaging as a mixture of micro- and nano-particles, coined 'micnobits' by Dimkpa and Bindraban (2016), can enhance nutrient availability to, and translocation within, the plant (Dimkpa et al. 2013; Subbaiah et al. 2016; Wang et al. 2012) of both particulate and dissolved ionic nutrients. Upon uptake, particulate micnobits release the active ions (Dimkpa et al. 2013). For other micnobits that dissolve prior to plant entry, uptake is dependent on solubility, which, because it happens at a slower rate than salts, could reduce immediate ionic losses from soils; reduce competition for transporter-driven ionic nutrient uptake; and potentially preclude accumulated ions from readily intoxicating the plant (discussed in Dimkpa and Bindraban 2016). Using particulate ZnO in soil applications, Watson et al. (2015) generated a Zn uptake efficiency of 37% in wheat grown in alkaline soil (pH 7.8), while excessively high uptake of Zn – >700%, relative to the control – resulted in phytotoxicity in an acidic soil (pH 4.5). With foliar treatments of nano Zn, Zn uptake efficiency of 24% has been recorded in cabbage (Xiong et al. 2014), and 11% in maize grain (Subbaiah et al. 2016). In another study, a formulation of micnobits containing ZnO, CuO and B_2O_3 enhanced grain Zn and B uptake efficiencies by 38% and 54%, respectively, under drought stress, where nutrient uptake from soil was severely hampered. However, in foliar applications the efficiency of Zn uptake, but not of B, was less from the micnobits than from ionic Zn (Dimkpa et al. 2017a). Strategically, micnobit-packaging in paint-like foliar fertilizers, and advancement into bio-nano packaging could boost nutrient use efficiency in the longer term (Monreal et al. 2015). Dimkpa and Bindraban (2017) reviewed the phytotoxicity of nanoscale nutrients and found that, when deployed as fertilizers at the right doses, toxic effects, if any, may be as inconsistent as effects observed with conventional fertilizers in different soils. In other words, the nano size of the material may be less critical in evoking toxicity than the exposure dose and environmental condition in different plant-soil systems.

In more field-practical application, plants such as bananas possess interesting characteristics that seem suitable for novel fertilization approaches to dramatically enhance nutrient uptake efficiency, while suppressing environmental perturbations, such as diseases, that lower yield. Banana production systems show high variability in response to soil-applied fertilizers. Moreover, bananas are heavily threatened by two major diseases (i) Black Sigatoka transmitted through an air-borne fungus, *Mycosphaerella fijiensis*, and (ii) Panama disease, caused by a soil-borne fungus, *Fusarium oxysporium* f. sp. cubense (Foc). Whereas some authors argue that addressing pest and disease infestation has priority over (NPK) fertilization, in order to prevent yield decreases (e.g. Smithson et al. 2001), others have reported secondary and micronutrient-containing fertilizers, including Ca, Mg, S and B, to reduce Sigatoka disease (Freitas et al. 2015, 2016). Moreira and Fageria (2009) demonstrated the positive effects of Zn fertilization on banana Zn content and yield using an application rate of 40 kg Zn ha^{-1} as $ZnSO_4$. Similarly, the application of B has been reported to enhance yield, with optimal application rates at 3.4 kg B ha^{-1} in the first cycle, and 1.3 kg B ha^{-1} in the second (Moreira et al. 2011). As a strategy to simultaneously increase yield and suppress fungal pathogen infection in banana, we hypothesize that foliar application, and/or injection of micronutrient suspensions into the corm could increase nutrient use efficiency, thereby addressing multiple production constraints. The basipetal flow of nutrients from the root or shoot starting points with the phloem or xylem stream (Wang et al. 2012) can provide plant-systemic effects that enhance resistance or improve tolerance to both soil- and shoot-borne diseases, while providing nutrients to drive banana productivity (Servin et al. 2015). A similar argument can, thus, be made for stem-injected nutrients which could flow acropetally with the xylem or phloem streams, to support carbohydrate formation in leaves and provide nutrition for fruit development, while inhibiting growth of the leaf or shoot pathogen. Relevant for this reasoning is the demonstration of P redistribution between mother and daughter banana plants (Cavalcante et al. 2005). Although Rodrigues et al. (2007) evaluated the effect of different proportions of ionic $ZnSO_4$ (20% Zn) and boric acid (17% B) applied directly in the cut-off seedlings of banana, and found hardly any impact on leaf nutrient content and crop performance, uptake and utilization could depend on how nutrients are packaged, resulting in a different outcome. Micnobit packaging would not only facilitate uptake and use of the cognate micronutrients, it would permit continuous availability of the nutrient in the plant system, due to slower but continuous dissolution of the constituent particles, compared to ionic forms that rapidly dissolve and become available all at once.

Another related approach to nutrient injection into plant stems could be the implantation, or infusion of plant stems with nutrients, which could rapidly supply plants with nutrients and/or nutrient-based pesticides. Scott et al. (2015) studied the effectiveness of commercially available liquid injections and implants of various pesticide (phosphoric acid-based) formulations of nutrients including K, Fe, Mn, Zn, B and Cu. Implant products of porous gelatin capsules were applied through holes drilled on the outer bark layer into the sapwood, and the liquid solution was injected using syringes that locked tightly onto the trees of *Banksia grandis* and *Eucalyptus marginata*. They reported significant reduction of disease lesions by the phosphoric acid with K implant and liquid injection, but found no statistically significant reduction with implants containing the micronutrients. Unfortunately, no additional growth related parameters were reported, to assess other potentially beneficial effects of the micronutrients. Larbi et al. (2003) found Fe sulphate implants in branches of Fe deficient peach trees to have a favorable effect on reducing chlorosis, even a year after the treatment. Ma et al. (1998) infused labelled N^{15} in maize stem internodes at anthesis, just below the primary cob. They observed rapid translocation of N towards dominant sinks, which, 3 days later, resulted in more than 40% of the N^{15} being located in the cob, husk, and kernels; 30% in leaves above the ear; and another 15–20% in the upper stem. Notably, by physiological maturity, 65–75% of the infused N^{15} had been deposited in the kernels. While these authors' interest was in exploring infusion for studying N translocation, their findings suggest that nutrients can be taken up through "infusion" in stems, and likely, barks, and that this could be an effective mechanism for rapid nutrient delivery to plants. This strategy could boost productivity in tree crops, like coffee or cacao. As the total amounts of all nutrients removed by cacao harvests are small, nutrient infusion, complemented with foliar application, may come into play for this crop, considering the tediousness of soil application of fertilizers (Van Vliet et al. 2015). With such an approach, trees in reforestation programs (e.g., the United Nations REDD program) could be instantaneously fertilized to allow, and sustain, production that can, in turn, help to regenerate degraded soils that are unable to sustain soil-applied fertilizer nutrients. While application in small food crops may appear unfeasible, developments in precision application with sensing technologies could allow automated injection into larger crops such as maize.

8 A comprehensive nutrient assessment to unlock fertilizer benefits

The societal view about the role of fertilizers to increase yields but at a huge environmental cost is rather limited and has not helped to catalyze a well-informed dialogue among policy makers, civil society, the research and private sector to push for the much-needed change in fertilizer technologies (Bindraban et al. 2015). In contrast to fertilizers, pesticides, for instance, have over the past decades developed from toxic, persistent chemicals, to targeted, systemic and bio-pesticides, based on a better understanding of the relevant biological processes, even up to the breeding of crops with enhanced resistance against pests and diseases. The evolution of pesticides has been a multi-stakeholder, society-wide process arising from concerns for animal and human health, and environmental degradation (e.g. "Silent Spring" by Carson in Carson 1962), and driven by heavy pressure from NGOs; strong government regulations and support for public research; and consequent significant private sector R&D investments (Barzman and Dachbrodt-Saaydehb 2011). At present, only modest innovations are introduced in fertilizers by the industry, such as with biostimulants, which are insufficient to mainstream the process of transformation.

Building on prior conceptual thoughts by Bindraban et al. (2015), Dimkpa and Bindraban (2016), and other review reports and papers about fertilizer products and fertilization technologies (see https://ifdc.org/vfrc-reports/), we, in this paper, present perspectives on smart balancing of nutrients and novel (bio-)chemical packaging of fertilizers along with creative delivery of fertilizer nutrients directly into plants, to unlock a broad spectrum of ecological and plant-based functionalities. Innovative fertilizer products and fertilization technologies will also contribute in mitigating the negative environmental impacts of fertilizers. Depending on how the technologies are implemented, the enhanced functionalities generated with innovative fertilizers could help to directly and indirectly drive the realization of several SDGs, including reaching zero hunger; improving life in water and on land; combating climate change; attaining good health, inclusive and sustainable economic growth; and responsible consumption and production.

Awareness among policymakers, NGOs, and the general public about the broad set of public good services that fertilizers can deliver, rather than its perception as a mere commodity, could catalyze a process of transformation of the fertilizer sector through public-private initiatives to unlock these potentials. Strong negative pressure could be exerted on fertilizers as with pesticides, but we argue that a positive perspective of multiple societal benefits and significant reductions in environmental problems could also drive the process of transformation in fertilizer design, development and use. A few global initiatives describe specific nutrient related challenges on N (Sutton et al. 2013) and P (Scholz et al. 2014) which unveil parts of the overall challenges. We call for drafting of a comprehensive nutrient assessment to set out the technicalities, as was done for water (Molden 2007) and biodiversity (FAO 1996), by a multidisciplinary research team that includes soil and plant scientists, environmental and climate change experts, chemical engineers, human nutritionists, epidemiologists, medical scientists, social and economic scientists, and representatives of other related sectors. Such an assessment will reflect upon and highlight the multifaceted implications of fertilizers as a fundamental driver of life on earth, and on how an effective and economically viable implementation of the technologies would set a solid foundation for well-informed dialogue for transformation in fertilizer products and technologies.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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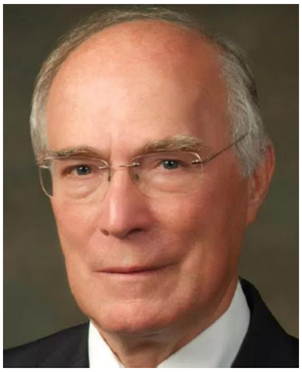

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