**OPINION**

Safeguarding human and planetary health demands a fertilizer sector transformation

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Societal Impact Statement

Fertilizer nutrients are essential for food and nutrition security, but a large proportion of nutrients applied to soil are lost because they are unavailable to plants. The extent of these nutrient losses exceeds safe and sustainable limits. Societal awareness of this is limited because it can take many seasons for nutrient-loss impacts to become visible. We propose that Innovative Fertilizers and Application Technologies (IFAT) could help reduce nutrient losses and thus reduce pressure on resources, and provide important micronutrients for human health. However, transformation of the fertilizer sector through stakeholder engagement, policy interventions, and public-private initiatives will be required to unlock the full potential of IFAT.

Summary

Strategies for delivering sustainable food systems require significant reduction in yield gaps and food system inefficiencies. Mineral fertilizers will play a critical role in achieving both of these aims. However, reduction in nutrient losses from mineral fertilizer use to levels that are considered sustainable has not been achieved and has been estimated to be unachievable, even with optimized practices for current products. We argue that Innovative Fertilizers and Application Technologies (IFAT) are needed to address the daunting and interlinked food, agricultural, and environmental challenges facing humanity and the planet. We define IFAT as a set of fertilizer products and technologies that are designed by taking the physiological needs of plants (such as nutrient uptake, redistribution, and utilization) as the entry point in the fertilizer development process, rather than starting first with chemistry. This approach aims for the timely and targeted delivery of nutrients in balanced quantities. We propose that this can result in multiple food, agricultural, and environmental benefits, including increased yield, improvements in nutritional quality, enhanced crop resilience, and reduced emission of greenhouse gases (GHG), and leaching losses. However, the benefits of IFAT for human and environmental health have remained

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elusive. The major challenge for optimal use of IFAT is a transformation of the vast fertilizer sector by means of government policy interventions, societal responses, and significant investment in public and private research and development.

KEYWORDS

fertilizer sector, human nutrition, innovative fertilizers, nanotechnology, plant health

1 | INTRODUCTION

Global hunger and malnutrition are epidemic intergenerational phenomena affecting billions of people. Among our greatest challenges is resolving this dire situation within the limits of our planetary boundaries (Rockström et al., 2009); defined as limits for the safe operating space for humanity beyond which deleterious or even catastrophic events will trigger nonlinear, abrupt environmental change within continental- to planetary-scale systems. A recent publication by The EAT-Lancet Commission on Food, Planet, Health (Willett et al., 2019; <https://eatforum.org/eat-lancet-commission/>) presents an alarming scenario of human and planetary health and calls for a Great Food Transformation: a significant change to a low meat plant-based diet and sustainable agricultural intensification are proposed as a means to contain environmental impacts within the limits of our planetary boundaries.

Mineral nitrogen (N) and phosphorus (P) fertilizers are essential for food production (Erisman, Sutton, Galloway, Klimont, & Winiwarter, 2008) and are among the major drivers of global change (Rockström et al., 2009). Decades of breeding for high-yielding crop varieties that respond to intensive N, P, and K (potassium) fertilization have increased crop yields. Higher yields have limited the need to expand the amount of arable land and have helped spare pristine ecosystems from being converted into land used for agriculture (Gibbs et al., 2010). However, nutrients not taken up by plants from the fertilizers are lost as ammonia and nitrous oxide to the air and as nitrate or phosphate to water bodies contribute to climate change, eutrophication, and biodiversity decline in coastal zones (Conijn, Bindraban, Schröder, & Jongschaap, 2018). To reduce nutrient losses, the fertilizer industry proposed the 4R nutrient stewardship (right source, rate, time, and place; IPNI, 2012). However, fertilizer use efficiencies remain low, at about 40% worldwide, ranging from less than 30% up to 70% (e.g., Bouwman et al., 2017; Zhang et al., 2015). Reformulation of bulk NPK fertilizers with coatings and encapsulations and the use of inhibitors have been demonstrated to slow nutrient release or prevent nutrient transformation, in the case of N from urea to ammonium and to nitrate, to control losses. However, the efficacy of fertilizers reformulated in this way remains unclear (Li et al., 2018). Moreover, polymer and bacterial coatings pollute the environment (Timilsena et al., 2015; Woodward, Hladik, & Kolpin, 2016). The specialized fertilizer markets of coatings and inhibitors, and of fertilizer products that contain secondary and/or micronutrients, such as calcium (Ca), magnesium (Mg), sulfur (S), zinc (Zn), iron (Fe), copper (Cu), manganese (Mn), and boron (B),

primarily serve high value crops in advanced production systems, while approximately 95% of the market caters solely N, P, and/or K (Research & Markets, 2017). Decades of policy measures to limit nutrient losses, such as those which have been in place in Europe since the mid-1980s, have improved the situation in specific geographical areas, but have been insufficient to reduce fertilizer-related problems. Independent studies using different methodologies, such as those by Willett et al. (2019) and Conijn et al. (2018), reveal that global nutrient losses to the environment will continue to exceed the safe operating spaces with respect to the planetary boundaries with current fertilizer products. Indeed, these nutrient losses are likely to exceed the planetary boundaries even with optimized agronomy combined with nutrient recycling, global redistribution (e.g., using less fertilizer in high-income nations and using more in low-income nations), and dietary measures (e.g., consuming more plant-based diets).

Decades of continuous cropping of improved crop varieties using only NPK fertilizers has risked the depletion of soil micronutrients that are essential for plant growth, as reported in India (Jones et al., 2013; Shukla et al., 2015). Jones et al. (2013) reported a consistent reduction in soil Cu, Zn, and Mn content over the past four decades in the relatively young soils of England, UK. These researchers also noted how the recommendation to treat only visible micronutrient deficiency symptoms results in the build-up of 'hidden or subclinical deficiencies' that may be limiting crop yields or livestock health, even without visible symptoms occurring. Therefore, yield increases along with reducing micronutrients through breeding (Bänziger & Long, 2000; Monasterio & Graham, 2000) and chronic micronutrient undersupply of crops have reduced the levels of secondary and micronutrients found in crops. For example, the levels of nutrients Ca, Mg, Zn, Fe, and Cu found in cereals, fruits, and vegetables have decreased, sometimes by more than half (Fan et al., 2008; Garvin, Welch, & Finley, 2006), which in turn impacts human nutrition.

To push nutrient losses back into the safe operating space, the EAT-Lancet Commission (Willett et al., 2019) calls for innovations at the systems scale to maximize high-quality production, and more specifically, for sustainable agricultural intensification to be based on radical improvements in nutrient-uptake efficiency. However, Willett et al. (2019) acknowledge that they have not included in their calculations the role of innovative technologies that are not yet proven at the large scale. This current article explores Innovative Fertilizer products and Application Technologies (IFAT); defined as a set of fertilizer products and technologies that are designed by considering the physiological needs of plants, such as nutrient uptake,

redistribution, and utilization, rather than chemistry as a starting point in the fertilizer development process. The aim of this is to ensure the timely and targeted delivery of nutrients in balanced quantities. A better synchrony between plants and fertilizer-nutrients ensures that IFAT encompasses the reduction in nutrient inefficiencies and losses; however, IFAT goes beyond nutrient management. It redefines the concept of fertilizer by advancing balanced-nutrient fertilization as an integrated system that responds to specific plant physiological challenges, individually or simultaneously. In theory, we conceive IFAT to provide multiple benefits. Thus, in addition to improving production (yields) and reducing the negative environmental footprint of fertilizers, the IFAT approach is designed to improve both the nutritional quality of edible agricultural produce and plant tolerance to both biotic and abiotic stresses. These responses are due to the enhancement of total uptake by plants of the multiple nutrients in balanced fertilizers. Taken together, these responses can result in numerous food, agricultural and environmental benefits, including enhanced crop resilience to challenging environments, facilitated plant phenological development, increased yield and human/animal nutritional quality, and reduced greenhouse gases (GHG) emissions, leaching losses and eutrophication.

2 | INNOVATIVE FERTILIZERS AND APPLICATION TECHNOLOGIES

Biological fixation of atmospheric nitrogen and soil weathering supplies plants with essential nutrients for their growth and reproduction. In addition, green manuring or cover cropping, and introduction of composted biomaterials contribute nutrients as well. However, these natural processes are insufficient to meet the global demands of food production without significant expansion of the amount of land devoted to the cultivation of crops (Connor, 2018; WRR, 1995). The majority of commercial fertilizers have been optimized for large-scale physicochemical processing, ease of logistics, and soil application for bulk NPK products (Bindraban, Dimkpa, Nagarajan, Roy, & Rabbinge, 2015). This creates a mismatch between the intended function of fertilizers for optimizing plant nutrition and their actual effectiveness. Combined with improved understanding of nutrient requirements, detection of nutrient deficiencies, and 4R nutrient stewardship, IFAT has the potential to improve the high inefficiencies associated with nutrient use by plants from current fertilizers. However, despite the low efficacy and environmental problems associated with the majority of fertilizer use, private sector investments in fertilizer R&D is $\approx 0.2\%$ of total product value, which compares poorly with the over 10% R&D investment seen in the seed and life sciences sectors (Fuglie et al., 2011). Several drivers maintain the status quo of the industry, such as a secured growth in the fertilizer market due to increasing demand for food, market concentration (Hernandez & Torero, 2013), geographically concentrated production, and recovery of high sunken costs in mining and production facilities. Importantly, nutrient losses are dispersed over land, water, and air, with a long lag time to reveal the adverse environmental

impact (e.g., Zhang et al., 2016). This causes a lack of societal awareness that is necessary to demand for change.

To address the mismatch between nutrient supply in fertilizer products and plant requirements, Bindraban et al. (2015) called for a paradigm shift in fertilizer design and delivery to plants by taking contemporary understanding of the plant physiological processes underlying nutrient uptake, redistribution, and utilization as a starting point rather than looking first at the chemistry. Similar “front-end” bio-based strategies for fertilizer design and delivery have also been discussed by Monreal, DeRosa, Mallubhotla, Bindraban, and Dimkpa (2015). Indeed, on-going work by these researchers describe a root exudate-activated system for N delivery, the design of which is based on specific plant root exudates that serve as temporal signals for the plants need for N. Figure 1 depicts the proposed reversal of the fertilizer design and development process. Fine-, bio-, and nanochemistry and advanced materials must be central to developing novel fertilizer products that supply balanced amounts of nutrients with temporal and spatial specificity to optimize plant utilization. Thoughtful formulations of multiple micronutrients can effectively increase both crop yield and nutrient content by exploiting synergism among nutrients (Bindraban et al., 2015; Rietra, Heinen, Dimkpa, & Bindraban, 2017). Novel fertilizer products and application technologies should also focus on nutrient uptake *via* above-ground organs, including leaves, seed dressing, and injection into the stem for crops with succulent and water-filled stems, such as bananas. These alternative application routes can reduce inefficiencies associated with leaching or volatilization, and fixation of nutrients in soil (Kah, Kookana, Gogos, & Bucheli, 2018; Rodrigues et al., 2017). Foliar application of micronutrients, such as Fe, Cu, Zn, and Mn, is already practiced, but their uptake can be enhanced when chelated with organic molecules, such as humic acid, or delivered as nanoparticles, for instance, with 60% higher uptake of Fe as compared with nonchelated Fe in soybean (Sharma, Malhotra, et al., 2019). Bacteriosiderophore chelated Fe applied to foliage resulted in enhanced grain Fe concentration by 1.7- and 2.0-fold in soybean and wheat, respectively (Sharma, Chandra, et al., 2019). Nutrients can be chelated by substances that respond to biological signals, such as root exudates, rather than to physicochemical soil conditions. Depending upon the needs of the plant, such signals will trigger the release of nutrients for uptake by the crop (Monreal et al., 2015). Similarly, biological insights can improve application strategies, for instance, complementing traditional soil Zn application to boost wheat yield with foliar Zn application that increases grain Zn content two- to threefold (Cakmak, 2008). Soil amendments such as sorbents (Chin et al., 2018) or beneficial microorganisms (Abbott et al., 2018) may enhance and synchronize nutrient availability to plant demand. Some micronutrients that are not essential for plants, like selenium (Se), are essential for humans and livestock, and increased contents of these micronutrients in crops benefit public health (Euroala, Ekholm, Ylinen, Koivistoinen, & Varo, 1991). IFAT approaches may prevent overdosing, such as by chelating or selecting the right formulations to prevent leaf burn (Noack, McBeath, & McLaughlin, 2010), or coating of NPK fertilizers with micronutrients

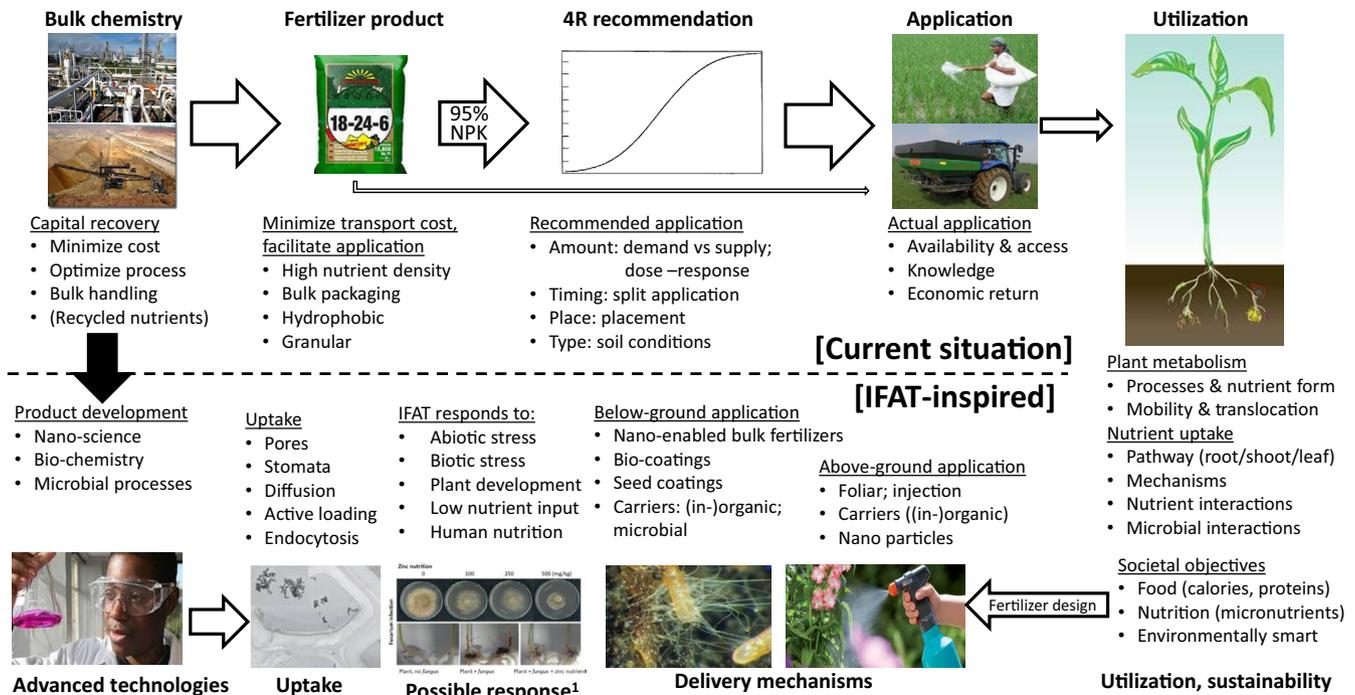


FIGURE 1 Upper panel: Current fertilizer system based on bulk production with generic chemistry. Lower panel: Innovative Fertilizers and Application Technologies (IFAT)-inspired reversal of the fertilizer design process that takes plant physiological processes, along with nutritional and environmental demands, as a starting point to achieve targeted delivery and specific responses. ¹See Dimkpa (2014), as an example of a systems response of IFAT to disease

for soil application rather than bulk blending (Dimkpa & Bindraban, 2018; Santos, Korndorfer, Pereira, & Paye, 2018).

An example of the need for IFAT is the formulation of urea-N with micronutrients, which can reduce N transformation via ammonia volatilization and nitrous oxide emission by 20%–35% (Khariri, Yusop, Musa, & Hussin, 2016). Comparable results are reported for coating with neem, nanorock phosphate, and nano-ZnO (Jadon et al., 2018). Reduced N losses as ammonia and/or nitrous/nitric oxide enhances crop uptake of N, which under a variety of production systems, including drought and low NPK inputs, have been recorded at between 8% and 53% (Dimkpa, Bindraban, et al., 2017; Dimkpa, Singh, Bindraban, Adisa, et al., 2019; Dimkpa, Singh, Bindraban, Elmer, et al., 2019; Dimkpa, White, Elmer, & Gardea-Torresdey, 2017b). The mechanism underlying micronutrients' influence on N uptake is related to their potential for modulating microbial ammonification or nitrification rates via influencing urease, dehydrogenase, and nitrification enzyme activities (Chaperon & Sauvé, 2007). Such an outcome could permit significant reduction in N application rates (Das et al., 2018; Dimkpa, White, et al., 2017b; Jadon et al., 2018). Invariably, the addition of micronutrient in fertilization corresponds with increasing total plant content of specific micronutrients (e.g., Zn from 85% to 500%), as well as helping to mitigate drought-induced reductions in plant development and productivity (Dimkpa, Bindraban, et al., 2017; Dimkpa, Singh, Bindraban, Adisa, et al., 2019; Dimkpa, Singh, Bindraban, Elmer, et al., 2019; Dimkpa, White, et al., 2017b). Such effects of a balanced nutrient approach rooted in IFAT can improve environmental and human health, and the resilience of

production systems under adverse environmental conditions such as drought. A second example elaborated by Bindraban et al. (2019) relates to the conversion of finite phosphate rock into water-soluble P fertilizers and also highlights the need for IFAT. These most common water-soluble P fertilizers readily bind to soil particles, restricting availability to plants. Excessive P fertilizer applications compensate such inefficiencies but often far exceed plant P demand for maximal growth and yield, suppressing uptake of Zn (Zhang, Liu, Li, Chen, & Zou, 2017a; Zhang, Liu, Liu, Chen, & Zou, 2017). Grains store excess P as phytate, which has human health benefits but also inhibits the bioavailability of Zn, Fe, and Ca. This could exacerbate nutrient deficiencies in people with unbalanced diets (Gibson, Bailey, Gibbs, & Ferguson, 2010). Hence, improving the nutritional value of staple crops through reduced phytate and increased Zn and Fe contents could drive P-based IFAT development. Low phytate content in Zn- and Fe-enriched crops would provide critical micronutrients in the low meat-intake, plant-based planetary diet proposed by the EAT-Lancet commission (Willett et al., 2019); currently, meat is the major source of these nutrients. Advanced material synthesis and formulation pathways could generate innovative products, such as P complexed to nanoscale Fe particles (Almeelbi & Bezbaruah, 2012) or microbial beneficiation of phosphate rock (PR) to release plant usable P (Goldstein, 2014). Microbial beneficiation of PR has been a subject of study for more than three decades. However, findings from evaluations under field conditions have been rather inconsistent. This is largely due to in vitro misidentification and misselection of true phosphate-solubilizing bacteria based on the use of tricalcium

phosphate, as opposed to using multiple metal-P compounds in tandem with tricalcium phosphate to reflect the entire gamut of P sources that microbes encounter in nature (Bashan, Kamnev, & de-Bashan, 2013a, 2013b). In terms of P product development, the possibility of formulating microbes truly capable of solubilizing PR together with ground PR and carbon sources for microbial growth could be explored, considering optimum environmental conditions for microbial survival in the formulation and the product shelf life (Bindraban, Dimkpa, & Pandey, 2020).

3 | SUSTAINABLE, RESILIENT, AND NUTRITION SENSITIVE AGRICULTURE

Meeting the nutritional demands of plants under prevailing soil, climatic, and cropping conditions through IFAT could yield multiple direct and indirect benefits to human and ecological health (Bindraban, Dimkpa, Angle, & Rabbinge, 2018). Crops nourished with balanced macro- and micro nutrients are more resilient to environmental stresses including drought (Dimkpa, Bindraban, et al., 2017; Dimkpa, Singh, Bindraban, Elmer, et al., 2019), parasitic weed infestation (Jamil, Kanampiu, Karaya, Charnikhova, & Bouwmeester, 2012; Rodenburg et al., 2011), and pests and diseases (Adisa et al., 2019; Servin et al., 2015). The application of micronutrients enhances the uptake efficiency of N and K (Dimkpa, Bindraban, et al., 2017; Dimkpa, Singh, Bindraban, Adisa, et al., 2019; Dimkpa et al., 2018; Dimkpa, Singh, Bindraban, Elmer, et al., 2019; Dimkpa, White, et al., 2017b), and mobilizes P in P-limited soils (Raliya, Tarafdar, & Biswas, 2016; Zahra et al., 2015). Improved plant nutrition enhances the cell wall structures of crop produce, which extends shelf life and subsequently reduces food waste (Ginzberg et al., 2012). IFAT-assisted closure of the yield gap could prevent ongoing expansion of agricultural land, contributing to the “zero-expansion aim” outlined by Willett et al. (2019). Preventing the clearing of natural ecosystems for agricultural land will avoid the accompanying 80%–90% decline in soil organic matter and associated CO₂ emissions (Zingore, Manyame, Nyamugafata, & Giller, 2005). The additional biomass generated from better plant nutrition can partially be incorporated into the soil for negative GHG emissions through carbon sequestration that comes with the cosequestration of N, P, and S (Angle, Singh, Dimkpa, Bindraban, & Hellums, 2017). IFAT as a cofactor for driving yield helps to increase crop water-use efficiency by four- to fivefold with a yield increase in cereals from 1 to 5 tons per hectare (Chander, Wani, Sahrawat, Pal, & Mathur, 2013; Chander, Wani, Sahrawat, & Rajesh, 2015; Molden et al., 2010). These gains are crucial where considerable yield gaps exist, such as in sub-Saharan Africa (e.g., Niang et al., 2017).

The potential contribution of IFAT toward alleviating human malnutrition is not well investigated. Of relevance is the analogy with multimillion-dollar investments in genetic biofortification, the increase in micronutrient content of crops through plant selection and breeding, with the promise of increasing micronutrient uptake by humans that is yet to be delivered (Saltzman et al., 2017). Based on published studies, a specific emphasis on micronutrients in IFAT can

simultaneously increase crop yields by 30%–70% or more; micronutrient content up to two- to threefold across crops and soil types (Das et al., 2018; Dimkpa & Bindraban, 2016; Dimkpa, Bindraban, et al., 2017; Dimkpa, Singh, Bindraban, Adisa, et al., 2019; Dimkpa, Singh, Bindraban, Elmer, et al., 2019; Dimkpa, White, et al., 2017b; Sharma, Chandra, et al., 2019); and crop tolerance to diseases by 30%–50% (Elmer et al., 2018; Elmer & White, 2016). To attain the highest efficacy, IFAT interventions should be tuned to location-specific soil–crop conditions (Kihara et al., 2017). In addition, IFAT can increase, multiple, rather than single, nutrients in plant and animal products. Micronutrient fertilization can mitigate 30%–50% of yield losses and maintain nutritional quality under drought (Bagci, Ekiz, Yilmaz, & Cakmak, 2007; Dimkpa, Bindraban, et al., 2017; Dimkpa, Singh, Bindraban, Elmer, et al., 2019), enhancing the resilience of the production system. Along the chain of agriculture and food processing, these nutrients enrich hundreds of downstream products. For instance, blending Se into fertilizers, as required by the Finnish government since the early 1980s, has increased Se content in more than 125 food items, including wheat, meat, and dairy products, with human intake increasing from 25 µg/day in 1975 to 124 µg/day in 1989 (Eurola et al., 1991). This meets the recommended dietary allowance for Se, while remaining well below the safe upper limit of 400 µg/day.

Joy et al. (2014) calculated the potential contribution of genetically biofortified crop cultivars (rice, wheat, maize, millet, beans, cassava, and sweet potatoes) with 30%–80% higher Zn content to human Zn intake. Replacing current crop cultivars would reduce the number of people with insufficient Zn intake from 12 million to below 1 million in Burkina Faso, Ghana, Niger, and Togo combined (Joy et al., 2014). We anticipate that similar impacts could be achieved with an IFAT-driven 50%–100% increase in Zn content of staple crops. Synergism between IFAT and the genetic biofortification of crops may generate even greater benefits to human diets and health (White & Broadley, 2009).

4 | TRANSFORMING THE FERTILIZER SECTOR

IFAT is an innovative and comprehensive approach that enhances the production and nutrient use capacity of food systems, with immediate outcomes and long-term sustained impacts. By default, IFAT is not confined to a single crop or cropping system but extends to different cropping systems and numerous products and segments within the food chain, thereby enhancing overall ecosystem health, and providing benefits across multiple sectors of society. Rather than being an end-of-process solution to remediate and recapture widely dispersed nutrients, IFAT is a front-end solution that prevents inappropriate use and uncontrolled loss of nutrients. When coordinated with advanced nutrient detection in soils or plants, agronomic efficiency measures, recycling, and global redistribution, IFAT has the potential to confine N and P losses within the safe operating spaces outlined by Rockström et al. (2009), while simultaneously reducing

pressure on water, land, and biotic resources and providing critical micronutrients in the plant-based and low meat diet proposed by the EAT-Lancet Commission (Willett et al., 2019). IFAT approaches are emerging that have proven to be effective under controlled conditions, with initial evidence for efficacy in field situations; however, widespread practical efficacy is yet to be demonstrated and implemented at scale.

To date, government policy interventions, Non-Governmental Organization (NGO) involvement, societal responses, and R&D investments have been insufficient to transform the fertilizer sector. Polemic debates over “excessive chemical inputs” have created a blind spot that has inhibited a well-informed dialogue among the actors to drive transformation (Geels, 2002). In analogy with the transformation of the pesticide sector (Barzman & Dachbrodt-Saaydeh, 2011), a multistakeholder, society-wide process arising from environmental and human health concerns compelled by NGOs, strong government regulations and support for public research, and consequent significant private sector R&D investments should transform the sector. In addition, rather than being considered as a generic bulk industrial commodity with large external costs, fertilizer sector transformation should be catalyzed through public-private initiatives to fully unlock the multifaceted benefits of IFAT to contribute to several of the United Nations Sustainable Development Goals, including goals 2, 3, 13, 14, and 15 (United Nations, 2015). Ultimately for IFAT to succeed, a concerted global effort at both local and national scales is required to validate and upscale the IFAT-based approach.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this study.

AUTHORS' CONTRIBUTIONS

P.S. Bindraban: main editor of overall paper and concept; C.O. Dimkpa: overall editing, reflections, and contributions on nanofertilizers; J.C. White: overall editing, reflections, and contributions on micronutrients for pest & disease resistance; F.A. Franklin: overall editing, reflections, and contributions on health relevance; A. Melse-Boonstra: reflections and contributions on human nutrition and health; N. Koele: reflections and contributions on microorganisms; R. Pandey: reflections and contributions on foliar applications; J. Rodenburg: reflections and contributions on sustainable agriculture; K. Senthilkumar: reflections and contributions on sustainable agriculture under field applications; P. Demokritou: reflections and contributions on material sciences; S. Schmidt: overall editing, reflections, and contributions on concept.

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