FOUNDATION FOR FOOD & AGRICULTURE RESEARCH®

Efficient Fertilizer Consortium

The Global Fertilizer Challenge: Future Directions for Efficient Fertilizer Research

FFAR EFFICIENT FERTILIZER CONSORTIUM

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Acknowledgements

The Foundation for Food & Agriculture Research commissioned this report to provide guidance for the development of the Efficient Fertilizer Consortium (EFC). The EFC is a multi-stakeholder consortium to advance research on novel and alternative fertilizers with the aim of improving understanding of the agronomic and environmental implications of new products. A task force, convened from January-May 2023, provided input into priority areas and relevant literature to this white paper.

This report was prepared by: Tai McClellan Maaz

Task Force Members
- **FFAR**: Allison Thomson
- **IFA**: Achim Doberman
- **ICL**: Nicolas Williaume
- **BASF**: Gregor Pasda
- **OCP**: Leonardus Vergutz
- **Nutrien**: Alan Blaylock
- **Mosaic**: Adam Herges
- **UK FCDO**: Áine McGowan
- **IFDC**: Kiran Pavuluri
- **CF Industries**: Kelvin Roth, Donald Thomas
- **Sound Ag:** Travis Bayer
- **Pivot Bio**: Natalie Hubbard

Introduction

The large-scale production of mineral fertilizers was a major agricultural advancement that helped increase crop yields to feed a growing population (Erisman et al., 2008) and mitigate agricultural land expansion. However, the uneven use of fertilizers has resulted in nutrient surpluses in many parts of the world yet severe shortages in other areas (Mueller et al., 2012), with inefficiencies leading to tradeoffs between crop and environmental goals (Mueller et al., 2014). Optimizing fertilizer inputs is not trivial and efforts are complicated by complex interactions and variability among plant, nutrient, edaphic, and climatic factors (Giller et al., 2011; Morris et al., 2018; Schut & Giller, 2020). Given the knowledge gaps in our understanding of these interactions across diverse regions and cropping systems, agronomic research on fertilizer use efficiency remains a top priority. A broader assessment of technology, data, and knowledge gaps is needed to help prioritize research and innovation that aim to understand and manage the more nuanced impacts of fertilizers within the context of biophysical constraints and variable crop nutrient demand. The results of this assessment will be used to inform research priorities for the Foundation for Food & Agriculture Research (FFAR) Efficient Fertilizer Consortium (EFC).

The primary objective of this white paper is to provide background and rationale for accelerating nutrient use efficiency research including the development of standardized methods for validation of efficiency claims for fertilizer products and formulations. Building on this, a secondary objective is to identify opportunities for innovation where additional investment would advance wider access to novel fertilizer products and solutions that increase nutrient use efficiency, reduce the environmental impacts from fertilizer use, and improve soil health. This white paper also aligns with the new paradigm of "responsible plant nutrition," which advocates for a circular economy and food system approach that includes novel fertilizer formulations and digital support tools as major action items (Dobermann et al., 2022a). The initial phase of the Consortium will not address all gaps identified in this assessment but will use this paper as a resource to help identify those specific topics that are of interest for pre-competitive research in a public-private partnership. The scope of this review is limited to mineral fertilizers, fertilizer enhancers, and/or additives with a focus on improving nutrient use efficiency. This review primarily seeks to identify research opportunities in regions where fertilizer use has been common for many decades, though we recognize that there are vast regions in which the main priority is to increase fertilizer use in order to achieve higher levels of productivity (Dobermann et al., 2022b). Nevertheless, these fertilizer innovations should ideally be applicable to all regions enabling underserved regions to efficiently increase their rates of nutrient application in an environmentally sustainable manner.

Essential plant nutrients

A history of plant nutrition

For almost one hundred years, we have defined elements essential to plant growth as (i) being necessary for the plant to complete its life cycle and (ii) directly involved in the nutrition of the plant which cannot be replaced by another element (Arnon & Stout, 1939). Plant scientists generally recognize 17 essential plant nutrients. Plants derived carbon (C), oxygen (O), and hydrogen (H) from the atmosphere and water, while soils supply the remaining which include nitrogen (N), potassium (K), calcium (Ca), magnesium (Mg), phosphorus (P), sulfur (S), chlorine (Cl), boron (B), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), nickel (Ni), and molybdenum (Mo) (Marschner, 2011). Other elements, such as selenium (Se) and sodium (Na), are considered beneficial but not essential (Havlin et al., 2017). However, Brown et al. (2022) argue that this narrow definition limits fertilizer research, regulation and practices, and these authors propose an updated definition with an expanded scope to include beneficial elements with demonstrable improvements in plant growth, quality, and resource efficiency:

"A mineral plant nutrient is an element which is essential or beneficial for plant growth and development or for the quality attributes of the harvested product of a given plant species grown in its natural or cultivated environment. A plant nutrient may be considered essential if the life cycle of a diversity of plant species cannot be completed in the absence of the element. A plant nutrient may be considered beneficial if it does not meet the criteria of essentiality, but can be shown to benefit plant growth and development or the quality attributes of a plant or its harvested product."

Humans have recognized the need for fertilizing crops with sources of plant nutrients for at least eight millennia, with archaeological evidence showing that farmers of the Neolithic period used manure for crop production (Bogaard et al., 2013). Francis Bacon, Hugh Plat, and Johann Rudolf Glauber first demonstrated the importance of mineral fertilizers—made up of saltpeter (potassium nitrate), lime (calcium carbonate), and phosphoric acid—for plant growth in the seventeenth century (Clericuzio, 2018). In the nineteenth century, chemist Carl Sprengel laid out the foundation for agricultural chemistry by providing empirical evidence for the essentiality of plant nutrients, and thus management, which Justus von Liebig popularized by putting forth his "Law of the Minimum '' (Ploeg et al., 1999; Tang & Riley, 2021). In 1842, the first fertilizer patent was given to John Lawes to produce a superphosphate fertilizer (Roberts, 2019). Yet, despite these developments along with the Haber-Bosch and Ostwald processes enabling ammonia and nitric acid manufacturing in the early twentieth century, large-scale production of fertilizers only accelerated after World War II (1940-1945) and particularly since the early 1960s; up until then, mineral deposits, manure, green manure crops, bone meal, blood meal and other organic sources served as the main sources of plant nutrients. At the end of the second world war, many countries transitioned from warfare to food security, and factories were repurposed to produce nitrogen fertilizers (Bekkerman et al., 2020). Other developments facilitated the growth of a fertilizer industry including the mechanization of farming equipment, investments in nutrient management research, development and release of improved crop cultivars, irrigation, acidulation of rock phosphate (i.e., phosphoric acid), expansion of potash mining operations, and technological innovations for extracting natural gas (Bekkerman et al., 2020; Evenson & Gollin, 2003; Hergert et al., 2015).

Human and environmental impacts of plant nutrients

Due to constraints on the capacity of soil to supply nutrients, commercial fertilizer products provide the majority of plant nutrients needed to sustain crop yields (Stewart et al., 2005). For nitrogen, researchers estimate that synthetic fertilizers feed about 50% of the global population (Erisman et al., 2008; Smil, 2004). However, despite its significant benefit to food production, unbalanced applications of fertilizers can have a multitude of negative environmental impacts. The nitrogen cycle (Figure 1), in particular, is inherently leaky (Firestone & Davidson, 1989), and reactive forms of nitrogen impact ecosystem and human health, including (i) air quality concerns due to the production of tropospheric ozone and particulate matter formation due to the presence of nitric oxide, nitrous acid, and ammonia in the atmosphere, (ii) acidification and loss of biodiversity in terrestrial systems due to the deposition of inorganic nitrogen, (iii) eutrophication and hypoxia in coastal ecosystems resulting from nitrate and phosphate enrichment, (iv) the contamination of groundwater by nitrate, and (v) the depletion of stratospheric ozone and increased atmospheric radiative forcing by accumulations of the greenhouse gas nitrous oxide (Braun et al., 2007; Galloway et al., 2003). From a monitoring perspective, the most important forms of reactive nitrogen to measure in agricultural systems include ammonia, nitrogen oxides (e.g., nitrate, nitric oxide, nitrous acid), and nitrous oxide (Luo et al., 2022).

In contrast to nitrogen, the biogeochemical cycling of phosphorus lacks a gaseous component and is dominated by mineral forms with low solubility (Liu et al., 2008). Nevertheless, phosphorus from soil can enter freshwater and coastal ecosystems by soil erosion, run-off, and leaching, resulting in the eutrophication of waterbodies (Carpenter, 2008; Chen & Graedel, 2016; Schindler et al., 2016). Water transports phosphorus from soils in a dissolved or particulate phase and as an inorganic or organic form. While phosphate molecules make up the inorganic phosphorus pool, dissolved phosphorus is operationally and arbitrarily distinguished from particulate phosphorus as the fraction passing through a 0.45 micrometer filter (Hart et al., 2004; Haygarth & Sharpley, 2000). The ratio of particulate versus dissolved and inorganic versus organic phosphorus transported through soil can differ, and monitoring efforts commonly measure multiple reactive pools of interest (Carver et al., 2022; Heathwaite & Dils, 2000; Kleinman et al., 2022). The amount of water-soluble phosphorus at risk of run-off and leaching is related to the degree of phosphorus saturation of a system; measurements of the aluminum and iron content that determines the capacity to retain phosphorus (e.g., sorption, precipitation) can help predict risk (Dari et al., 2018; Nair, 2014).

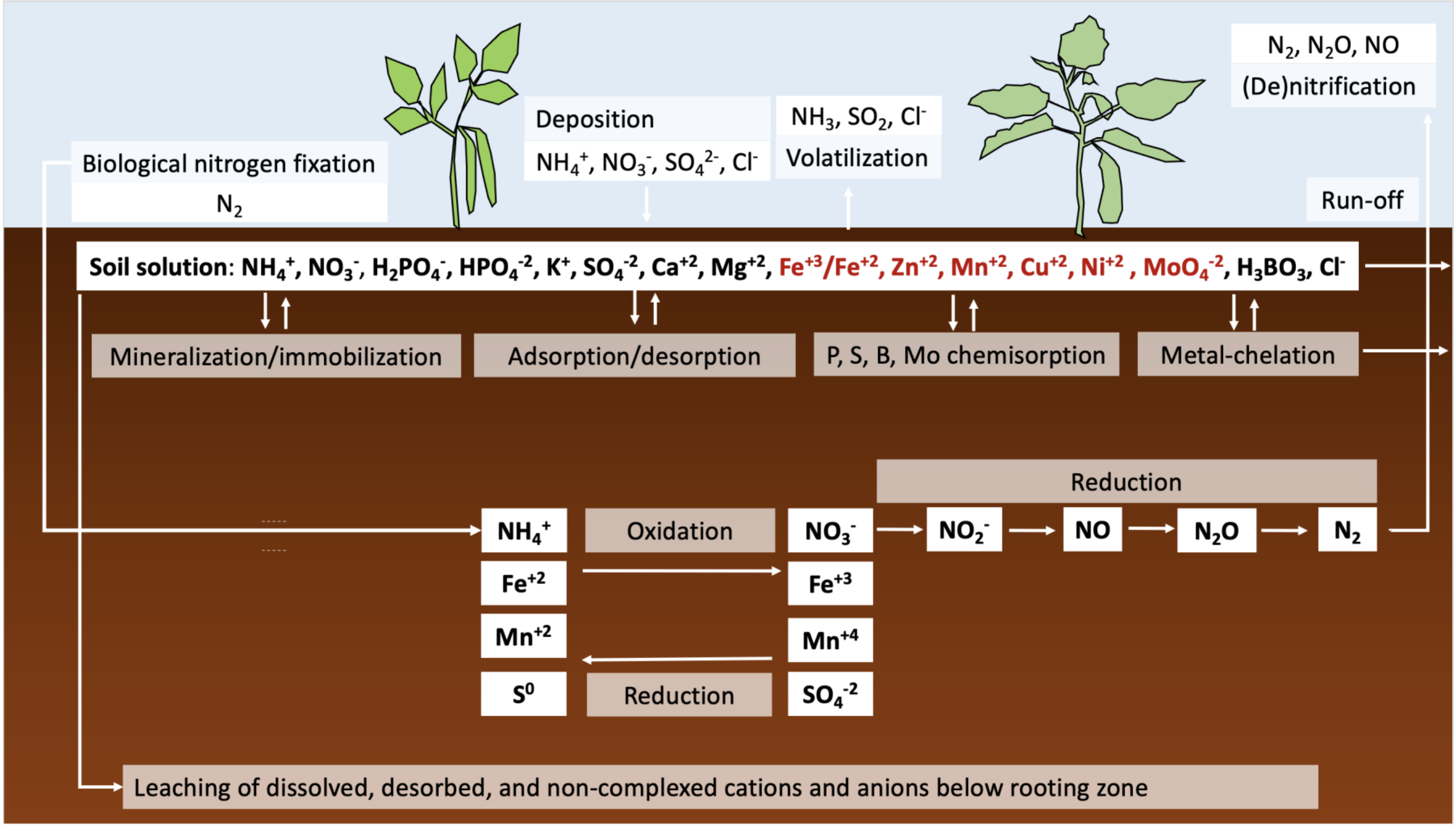

Figure 1. The cycling and losses of essential plant nutrients in soil-plant systems.

Regarding other plant nutrients, potassium–similar to other base cations such as calcium and magnesium–has not been identified as an environmental pollutant (Brouder et al., 2020). However, potassium is soluble and can leach to groundwater or to surface waters (Goulding et al., 2020). In contrast, sulfur deposits from the atmosphere result in the acidification of terrestrial ecosystems and cation leaching, and thus can contribute to nutrient deficiencies and a decline in soil health (Liu et al., 2022; Tomlinson, 2003). In aquatic sediments, there is some evidence that an increase in sulfate supply to sulfate reducing bacteria might correspond with elevated methyl mercury (HeMg), which can bioaccumulate in the food web (Hinckley et al., 2020). Sulfide can be toxic to plants unless precipitated with iron; however, the precipitation reaction may then free up phosphorus from iron phosphates under reducing conditions, which can thereby indirectly contribute to the eutrophication of aquatic ecosystems (Hinckley et al., 2020).

Copper, zinc, manganese, iron, molybdenum, nickel, and boron are essential plant nutrients that are also categorized as trace elements. Plants generally require these elements in low concentrations and within narrow ranges, and so excess applications can lead to plant toxicity, heavy metal contamination in the soil, and impacts on human health (Chrysargyris et al., 2022; Hunter, 2008). Other trace elements are toxic to plants and categorized as soil contaminants, including cadmium, lead, chromium, mercury, and arsenic, but may enter soil as impurities in fertilizers or organic amendments (He et al., 2005). Total metal concentrations in the soil poorly predict the toxicity of micronutrients and other trace elements, and instead metal speciation and bioavailability models are needed to determine toxicity thresholds (Smolders et al., 2009).

Evaluation of nutrient management

Excessive or insufficient fertilization combined with improper agronomic practices can have multiple unintended environmental consequences due to the complex interactions among plant, nutrient, edaphic, and climatic factors that complicate management decisions (Defries & Nagendra, 2017). Because of the complexity of agronomic management decisions, there is a need for high quality data to link fertilizer practices with performance goals of optimizing crop production while minimizing environmental losses across diverse climates, soils, and cropping systems; and ultimately, to develop strategies for optimal fertilizer use. However, a shortage of multidisciplinary data and lack of standardization hinders our ability to advance these goals (Eagle et al., 2017). The prospect of identifying new technologies with the potential to increase fertilizer use efficiency is contingent upon the adoption of a framework for rigorous evaluation of product efficacy. Development of such a framework will benefit the innovation process by demonstrating baseline data for widely used mineral fertilizers and provide test data for selected novel product innovations, combinations of products, and in-field farming practices. A rigorous evaluation framework of fertilizer products and nutrient management tools will also achieve two goals: (1) to accelerate the innovation process by obtaining reliable, cost-efficient information on the field performance of candidate innovations (e.g., products, practices, integrated solutions), and (2) to robustly evaluate these innovations across key regions for purposes of market development, agronomic guidance for farmers, government registration of products, environmental certification, etc. The first objective occurs earlier in the innovation process and along the laboratory to field pipeline, likely requires different protocols depending upon the most relevant parameters of interest, and follows an interative process before proceeding to a larger scale. In contrast, the second objective might include field evaluations at the end of the innovation process but may also include the re-testing of existing innovations to obtain reliable data for new purposes such as certification based on environmental performance metrics. The need for evaluation frameworks is urgent because many novel products are entering the markets (patent search results in Supplemental 1, Supplement 2), including products in which a clear mode of action is often not understand, or the mixtures of substances or practices confound our attempt to isolate effects.

The selection of methods for fertilizer testing—or what and how to measure—is not trivial. While standardized experiments can facilitate comparisons across treatment groups and locations, a researcher must first determine whether fertilizer treatments even make sense within the context of divergent conditions that farmers face (Krupnik et al., 2019). For example, a researcher investigating the performance of an alternative fertilizer source should ideally compare the effects to a conventional source under a set of practices that optimize the performance of that conventional fertilizer, or else relative differences might be overstated (Cassman, 2007). This may be challenging given that best management practices vary depending upon the specific production environment and cropping system. Furthermore, while research tends to focus on categorical comparison between fertilizer sources, management practices, or systems, these categories are often difficult to define and, in reality, exist along gradients. Lastly, the scaling of research findings is another barrier to leveraging data across experiments. The laboratory to field pipeline is designed to incrementally demonstrate proof-of-concepts for fertilizer efficacy by scaling up with each experiment (Figure 2). However, if the field research only involves plot-level research, the results must be extrapolated to a larger farm scale at which it was not measured (Krupnik et al., 2019).

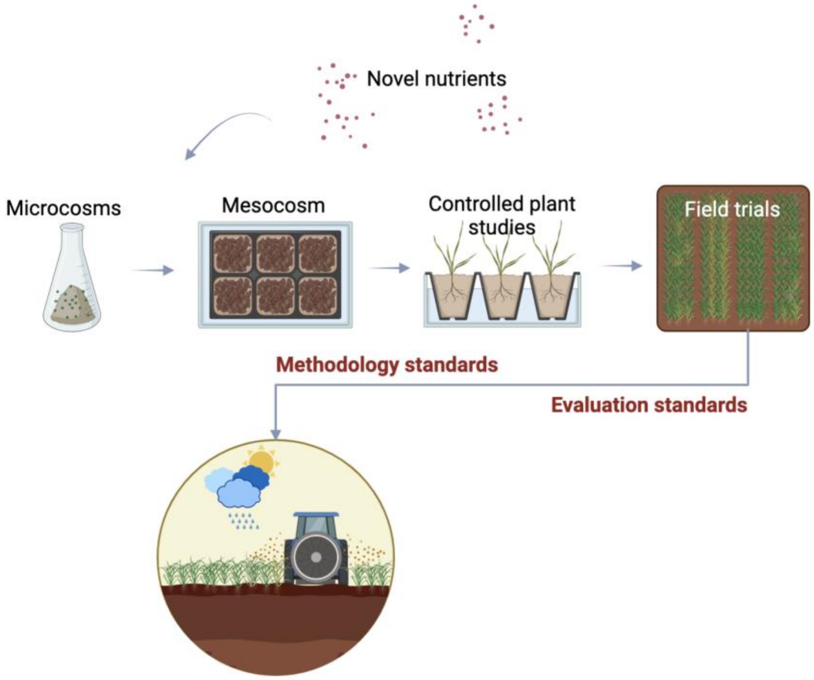

Figure 2. The evaluation of novel fertilizer products and practices across the laboratory to field pipeline.

Nutrient management research is complex and requires coordinated approaches that often involve transdisciplinary teams working across wide geographies. This coordinated research involves an experimental network, properly defined treatments and variables of interest, standardized protocols, minimum data requirements with supporting metadata, and a database for storage and sharing beyond the project participants (Herzmann et al., 2014;

Kladivko et al., 2014). Transparency in the criteria of methods (Haddaway & Rytwinski, 2018) and making data more widely available from coordinated research experiments in a repository can facilitate efforts for quantitative synthesis. Datasets are now recognized as scholarly products that can be published in data journals (Walters, 2020), helping overcome publication biases that might limit generalizability of the results (Philibert et al., 2012).

Development of minimum standards

Coordinating the evaluation process can serve scientific innovation as well as industry by producing data for new purposes in an independent and standardized manner.
This process should start with developing minimum standards for experimental target data elements within properly designed experiments and data collection procedures to compare fertilizer treatments (Cassman, 2007). Cassman (2007) argues that, at the minimum, agronomic studies should report food output per unit area per unit time. Likewise, environmental assessments should present elemental losses per unit area per unit time. Any comparison of nutrient sources should quantify the total nutrient input levels and equalize them as needed, which is especially important for comparing elementally simplistic fertilizer sources with full-spectrum organic sources or blends. Finally, studies should design experiments to account for random variation across space and time, properly replicate treatments, and include the proper treatment control(s). Experimental designs should also standardize the length and spatial scale of experiments (Bolinder et al., 2020) and identify higher level factors that might explain random differences among sites or groups (Bolinder et al., 2020; Maaz et al., 2021).

Definable treatments and data requirements

Efforts to test and evaluate fertilizer products and practices must first properly define treatments and explicitly-state data collection requirements, which will facilitate coordinated research efforts and generate data that can be seamlessly combined and reported across a larger temporal and spatial extent (Eagle et al., 2017). Research teams and programs can set up data dictionaries that explicitly define the terms, units, and other attributes of data collected from field experiments (Brouder et al., 2019). Data dictionaries provide consistency in data collection and use, aid interpretation, put forth conventions, and help establish data standards. However, the complexity of data and protocol standards might depend upon the end user and whether the goal is to use the data for research versus commercial applications. For instance, complex ontologies might be of interest to scientists and modelers but less useful for practical innovation purposes.

Part of this process is determining the data that evaluators must report. For instance, Slaton et al. (2022) proposed minimum dataset and metadata guidelines for the development of fertilizer recommendations, including the required (and recommended) measurement and reporting of soil chemical and physical properties, experimental design elements, and metadata detailing soil sample collection and field trial information. Likewise, Eagle et al. (2017) proposed a set of minimum requirements, as well as a more expansive set of preferred requirements, to examine environmental outcomes. These researchers provided guidance on reporting various types of data, including management, soil, weather, crop, nutrient loss, economic, and methodology data. These exhaustive lists of recommendations provide a starting point from which to guide experimental design and data collection for testing fertilizer products (Eagle et al., 2017; Slaton et al., 2022). While previous research has typically centered upon the agronomic and environmental impacts of nitrogen and phosphorus, novel fertilizer research might include the assessment of additional essential plant nutrients as well as biostimulant relevant parameters, including the leaching of base cations, the toxicity of micronutrients, presence of heavy metal contaminants, and soil health. It is also important to mention that new platforms for field trial and data management are increasingly available to aid and even automate data collection and reporting.

Common standardized protocols

The evaluation of the environmental outcomes of fertilizer products must follow robust and acceptable protocols. Complex projects might have numerous parameters of interest, each with their own methods of measurement (i.e., raw values) and approaches of data synthesis (i.e., calculated values). For soil and plant measurements, projects may need to specify soil or plant sampling protocols, preparation, and laboratory analyses (Kladivko et al., 2014). For in-field monitoring of environmental losses, multiple methods and instruments may be available, and the preferred approach may factor in site specification, scale of research, costs, required expertise, and time. For instance, ammonia volatilization is commonly measured by five methods, including the enclosure method, the venting method, the continuous airflow enclosure method, the wind tunnel method, and by micrometeorological methods (Yang et al., 2018). While the venting method seems to be most common and affordable, the determination of the proper method may depend on the research goals. For nitrous oxide emissions, the non-steady state, non-flow-through closed chamber technique predominate (Clough et al., 2020) with recent efforts focused on automating measurements (Grace et al., 2020). However, non-steady-state through-flow chamber and steady-state through-flow chamber chamber designs are also available (Pumpanen et al., 2004). Like ammonia volatilization, micrometeorological techniques can help address challenges with the small footprint of chamber-based measurements (Flesch et al., 2018). Simulation models can be used to evaluate the risk associated with fertilization (Basso et al., 2012), and researchers can use metamodels based on process models to explore the environmental mitigation potential of changes in fertilizer management (Kim et al., 2021). Researchers might integrate models into protocols to estimate specific losses which are not citrical or cost-effective to measure at larger scales. However, models must still be calibrated to site conditions, and require sufficient data on the behavior of the fertilizer product or practice of interest to adjust specific parameters that drive nutrient cycling dynamics (Shi et al., 2022).

A variety of techniques also aim to measure the transport of dissolved/particulate and inorganic/organic nutrients in soil water. Methods for quantifying nutrient concentrations in the soil solution include direct sampling via soil cores, drainage lysimeters, porous ceramic cup soil-water samples, adsorbents, from tile drain outflows, or groundwater wells (Snyder, 1996). Though differences in the absolute values of losses are observable, studies have demonstrated similar patterns or relative differences among the different techniques (Bergström, 1987; Wang et al., 2012; Zotarelli et al., 2007). In the absence of direct flow measurements (e.g., drainage lysimeters), nitrate leaching can be determined by multiplying the nitrate concentration in soil solution (e.g., collected with porous cups) with modeled or calculated drainage volumes based on estimated water balances (Cui et al., 2020; Ramos et al., 2001; Vogeler et al., 2020).

With regard to other essential plant nutrients, the toxicity of micronutrients and other trace elements is poorly predicted by total metal concentrations in the soil as previously discussed. Instead, researchers recommend an assortment of soil extraction protocols to determine bioavailable metal concentrations. For example, solutions such as Mehlich 1 and $CaCl_2$ may extract exchangeable metals while other may be appropriate to extract metal fractions complexed with carbonate and organic fractions (e.g., EDTA and DTPA) (Wang et al., 2021; Xu & Fu, 2022).

Proper experimental controls

The inclusion of well-defined, proper controls is essential to interpret the results of any fertilizer experiment. For fertilizer product research, at least two types of controls should be considered (i) a treatment without any fertilizer added, and (ii) a treatment with a conventional fertilizer product provided at the equivalent nutritional levels as the alternative source. Ideally, a range of application rates would be tested to capture crop yield response. If fertilizer timing or placement differs between fertilizer sources, additional controls should also be considered (Eagle et al., 2017). For example, for evaluating a foliar product, a proper control would receive the soil application but must also be sprayed with a non-nutrient containing water solution applied in the same rates and times as the foliar fertilizer. In addition to proper controls, the reporting of additional covariates or explanatory factors—though not of primary concern to the response within the context of the individual experiment—may help evaluate the variability in the crop response to fertilizer treatments due to differences in baseline soil fertility status, soil type, application rates and other management practices, and weather conditions (Eagle et al., 2017).

Alternative experimental designs and advanced statistical analysis

Traditional experimental designs and statistical analysis commonly utilized in agricultural research often rely on full factorial designs and replication within space and time. Plant breeders have long grappled with the space and time constraints that full factorial, replicated designs encounter, and so researchers have developed augmented methods to assess plant performance (Federer & Raghavarao, 1975; Neyhart et al., 2022; Zystro et al., 2019). Likewise, ecologists widely use space-for-time substitutions as an alternative for long-term (time-for-time) experiments (Blois et al., 2013; Pickett, 1989). Macroecological and plant genetic studies also indicate that researchers can sacrifice within-group or site replication in broad investigations of populations or ecological conditions - in other words, design more extensive rather than intensive experiments (Castle et al., 2019; Lorenz, 2013). Therefore, an alternative design for a fertilizer trial may include experimental units within nested structures and treatment designs that allow for the substitution of space for time (Li et al., in review). In coordinated research programs over wide geographies, advanced statistical tools can facilitate data synthesis efforts across varying spatial and temporal scales, including techniques such as multilevel modeling (Qian et al., 2010) and structural equation modeling (Smith et al., 2014; Wade et al., 2020). A key consideration for new designs for the standardized evaluation of novel fertilizer solutions is that – besides being agronomically and environmentally sound and robust – it must be cost efficient and operational, allowing rapid evaluations to guide research, extension, and commercial development.

Enhanced efficiency fertilizers

The need for enhanced efficiency fertilizer products was quickly realized from the impacts of soil properties and crop growth on variable nutrient demand at different crop phenologic stages and the existence of many nutrient loss pathways. Dating back to the 1960s, slow- or controlled-release fertilizer products were conceptualized to better synchronize nutrient release with the nutrient demand of plants. These fertilizers included coated products (e.g., sulfur coated urea), sparingly soluble products (e.g., urea formaldehyde), bioactivated products (e.g., cortonylidenediurea), and chemical or physical carrier products (e.g., ammoniated coal) (Oertli, 1980). Controlled-release products, which claim to control the rate, pattern, and duration of release, are sometimes contrasted to slow-release fertilizers that are not necessarily well-controlled (Shaviv & Mikkelsen, 1993). Some of the mechanisms that control the release of nutrients include diffusion, chemical reactions, swelling, and osmosis (Shaviv, 2001). The International Fertilizer Association (IFA) defines slow-release fertilizers as products that release nutrients at a slower rate than its reference via biological, chemical, or biochemical mechanisms (2020). This definition encompasses sparingly soluble, bioactivated, and some coated products. In contrast, IFA distinguishes controlled-release fertilizers as products that release nutrients at a controlled rate relative to its reference through physical mechanisms such as coatings, encapsulation, or occlusions (IFA, 2020).

Controlled-release products are also differentiated from another type of enhanced efficiency fertilizer technology - enzyme inhibitors (e.g., urease and nitrification inhibitors) designed to stabilize nitrogen sources by temporarily slowing the biogeochemical transformation of urea or ammoniacal fertilizers (Amberger, 1989; Hauck, 2015; Shaviv & Mikkelsen, 1993). Urease inhibitors temporarily slow the enzymatic hydrolysis of urea in soils by depressing or preventing the transformation of amide-N to ammonium hydroxide and ammonium, while nitrification inhibitors delay the oxidation of ammonia to nitrate by suppressing the ammonia monooxygenase enzyme (Trenkel, 1997).

There is ample evidence that controlled-release and stabilized fertilizers lead to positive agronomic and environmental outcomes. Sufficient research has been conducted to support a number of meta-analyses designed to identify broad conclusions; however, any analysis of trials conducted under different research protocols comes with a range of uncertainty. Meta-analyses have indicated that yields are greater on average when fertilizer is physically protected (Linquist et al., 2013; Zhang et al., 2019) or treated with urease and/or nitrification inhibitors (Abalos et al., 2014; Burzaco et al., 2014; T. Li et al., 2018; Linquist et al., 2013; Qiao et al., 2015; Quemada et al., 2013; Silva et al., 2017; Thapa et al., 2016). In a re-analysis of synthesized data, Rose et al. (2018) reported that the highest yield differences between fertilizers treated versus untreated with nitrification inhibitors were greatest at suboptimal fertilizer rates. This finding suggests that future studies should not only examine comparative differences between enhanced efficiency fertilizers and their conventional counterparts, but also examine impacts with varying rates of fertilizer addition. Furthermore, in their meta-analysis, Burzaco et al. (2014) noted that the probability of yield gains and increases in plant nitrogen uptake was only 56% and 65%, respectively, in response to nitrification inhibitors.

Several meta-studies have also synthesized the environmental impacts of enhanced efficiency fertilizers. In a second-order meta-analysis, Lam et al. (2022) concluded that enhanced efficiency products reduced nitrate leaching by 17-58%, ammonia volatilization by 50-74%, and nitrous oxide emissions by 28-49%. One exception, however, was nitrification inhibitors which increase ammonia emissions though effectively reducing nitrous oxide emissions and nitrate leaching (Lam et al., 2017; T. Li et al., 2018; Pan et al., 2016; Qiao et al., 2015). Nevertheless, the inclusion of both urease and nitrification inhibitors was effective at preventing this trade-off (Lam et al., 2022). The efficacy of nitrification inhibitors mitigating nitrous oxide losses is also similar across different types of inhibitor compounds and fertilizer sources, including both inorganic and organic fertilizers (Soares et al., 2023). These results were confirmed by two other second-order meta-analysis studies, which reported that enhanced efficiency fertilizers consistently reduced nitrous oxide emissions in agricultural soils (Grados et al., 2022) and had the largest impact increasing crop yields and nitrogen uptake, while reducing nitrous oxide emissions, ammonia volatilization, and nitrogen surplus (Young et al., 2021). While not examined in these meta-analyses reviews, future efforts should identify if enhanced efficiency products provide a means to reduce agronomic optimal fertilizer rates and achieve other long-term goals such as producing more nutritious food and improving soil health. Gao & Cabrera Serrenho (2023) purport that the deployment of enhanced efficiency products is part of a strategy to increase nitrogen use efficiency, which in combination with decarbonizing fertilizer production, might offset greenhouse gas emissions from nitrogen fertilizers by 20% by 2050.

Despite strong evidence for the beneficial impacts of enhanced efficiency fertilizers (Table 1), controlled and stabilized fertilizers products make up a minority of the fertilizer market. Cost is often cited as the major barrier to large-scale adoption (Timilsena et al., 2015). Additional barriers include environmental concerns associated with the use of non-biodegradable plastics commonly used in some products. Identifying alternative organic materials to replace plastics in these products is a growing area of research. Moving forward, the criteria for novel fertilizer products to break into the mainstream market might include products and formulations (1) that meet the nutritional requirement of the crop, (2) include biologically meaningful release mechanisms, (3) that can be easily and safely transported, stored, and applied, (4) are environmentally safe, and (5) can be manufactured at scale. In the following section, we will explore novel fertilizer products which may help enhanced efficiency fertilizers break through to the mainstream market. Then, given that the complexity of products might also hinder the ability of a farmer to select the right product for their operation and maximize their effectiveness, we will review technological packages that better match fertilizer release with the complete nutritional demand of the crop.

Table 1. Synthesized results from meta-analyzes examining the impact of enhanced efficiency fetilizers (EEF) on yield and enivronmental outcomes.

EEF Type†	Yield increase	NH_3 decrease	N_2O decrease	NO_3^- leaching decrease	Meta-analyses
Non-urea/mix		31-75% (n=1)			Pan et al., 2016
UI	2-10% (n=5)	22-97% (n=6)	0-49% (n=4)	39% (n=1)	Thapa et al., 2016; Linquist et al., 2013; Abalos et al., 2014; Saggar et al., 2013; Snyder et al., 2009; Pan et al., 2016, Dimkpa et al., 2020; Li et al., 2018; Silva et al., 2017; Lam et al., 2022
NI	2-14%‡ (n=9)	-3 to -65% (n=5)	8-96% (n=8)	17-58% (n=4)	Quemada et al., 2013; Thapa et al., 2016; Linquist et al., 2013; Abalos et al., 2014; Qiao et al., 2015; Snyder et al., 2009, Lam et al., 2017; Pan et al., 2016, Dimkpa et al., 2020; Li et al., 2018; Burzaco et al., 2014; Rose et al., 2018‡; Han et al., 2017; Young et al., 2021
UI + NI	0-9% (n=6)	13-87% (n=3)	0-50% (n=4)	-51 to 58% (n=2)	Thapa et al., 2016; Linquist et al., 2013; Abalos et al., 2014; Snyder et al., 2009; Dimkpa et al., 2020; Li et al., 2018; Lam et al., 2022
CRU	5-7% (n=2)	39-83% (n=4)	8-77% (n=3)	17-92% (n=2)	Linquist et al., 2013; Pan et al., 2016; Zhang et al., 2019; Han et al., 2017; Lam et al., 2022

†UI = urease inhibitor; NI = nitrification inhibitor, CRU = controlled release (e.g., polymer coated).

‡Nitrification inhibitors which increase ammonia emissions though effectively reducing nitrous oxide emissions and nitrate leaching.

Novel fertilizer products

An emerging suite of fertilizer technologies come under the umbrella of "smart" fertilizers that can more broadly be conceptualized as innovative products that aim to improve nutrient use efficiency. However, as a new frontier, the term "smart fertilizers" is poorly defined in the literature. Raimondi et al. (2021), for example, propose the following definition:
"[a] smart fertilizer is any single or composed (sub)nanomaterial, multi-component, and/or bioformulation containing one or more nutrients that, through physical, chemical, and/or biological processes, can adapt the timing of nutrient release to plant nutrient demand, enhancing the agronomic yields and reducing the environmental impact at sustainable costs when compared to conventional fertilizers." We would emphasize that plants should trigger the release of nutrients from smart fertilizers through mechanisms such as bioactivation by soil microorganisms in the rhizosphere or response to plant signals. In addition to crop yields, the nutritional quality of the crop is an important outcome as well.

The research and development of smart fertilizers might involve investment in novel ideas or mechanisms. Technologies on the forefront include the identification of novel physical and biochemical controls on nutrient release such as new formulations of fertilizer coatings as well as next generation biochemical inhibitors and analogues (Lam et al., 2022). Microbial approaches can also fall under the umbrella of smart fertilizers and might highlight the discovery of bioactivation pathways. Though still in its infancy, plant-oriented approaches are also on the horizon, which include incorporating plant signaling or biosensor molecules into fertilizer products. And though perhaps secondary to mechanisms that control the release of nutrients, biostimulant research can provide insight into fertilizer technologies that promote plant growth under the more inclusive definition of plant nutrients (Brown et al., 2022).

Smart fertilizers tend to include one or more of the novel technologies, which makes the categorization of smart fertilizers challenging. In this review, we group novel fertilizer products into three general categories as proposed by Calabi-Floody et al., (2018) and explored by Raimondi et al. (2021). This includes (1) nanoscale fertilizers, (2) bioformulations, and (3) enhanced efficiency fertilizers that control the release of nutrients physically (i.e., controlled release) or biochemically (i.e., stabilized forms) (Figure 3). However, it is important to note that there is a great degree of potential overlap among these categories. In the following sections, we will define each of these categories, provide a brief description of the mechanism that controls nutrients release, summarize the impacts on yields and environmental outcomes, and identify potential limitations to commercialization.

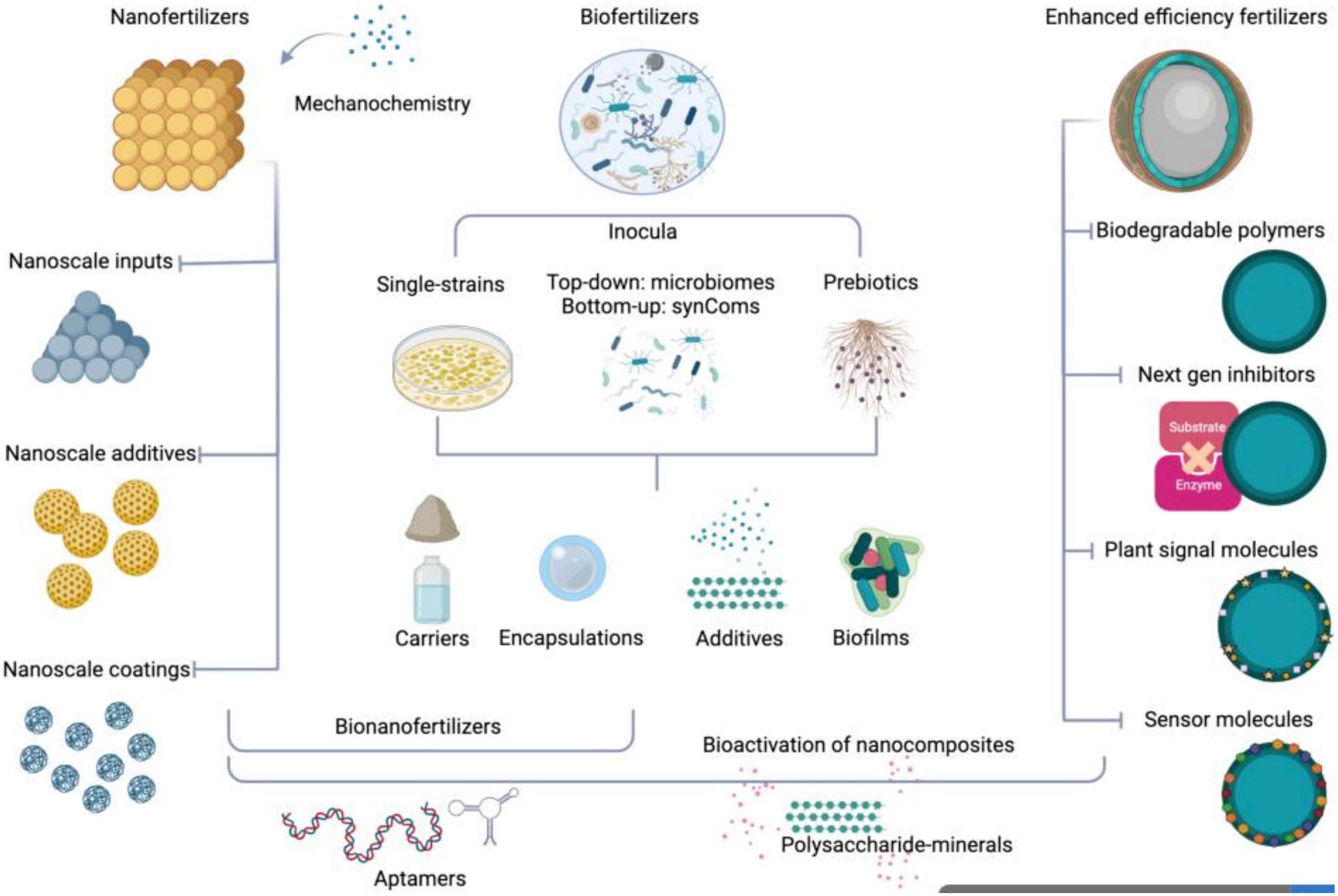

Figure 3. Three categories of novel fertilizer products include nanofertilizers (left), biofertilizers (center), and enhanced efficiency fertilizers (right) with the different subcategories and/or approaches of each novel type. Created in BioRender.

Nanofertilizers

Definitions and modes of actions

By definition, nanoscale particles range between 1 and 100 nm (Mastronardi et al., 2015). However, the usage of the term nanofertilizers is poorly regulated, and marketed fertilizer products may exceed this specification despite their use of the term "nanoscale." The primary argument for nanofertilizers as efficient fertilizers is that the high surface area and small size of the fertilizer molecules enhances the uptake of nutrients by plants through nanoscale pores in plant tissues, complexation with transporters or root exudates, and exploitation of ion channels (Derosa et al., 2010). Alternatively, nanostructures that encapsulate soluble fertilizers may control the release of nutrients (Marchiol et al., 2020). Nanomaterials can be produced at low cost and at scale through top-down approaches which utilize physical or chemical processes to grind, etch, or mill bulk materials to nanoscale particles or emulsions (Mastronardi et al., 2015). Mechanochemistry methods can also yield nanoscale productions (Zheng et al., 2021). This is in contrast to bottom-up approaches that involve smaller building blocks at the atomic or molecular scale to create nanoscale materials through self-assembly. Alternatively, nanofertilizers can be produced through biological or "green" synthesis methods (Dimkpa & Bindraban, 2018). As outlined by (Mastronardi et al., 2015) there are three main types of nanofertilizers:

> (1) Nanoscale fertilizer inputs: Bulk macronutrient and micronutrient fertilizers are reduced to nanoscale products via mechanical or chemical processes. The formulation of nanoscale inputs typically includes additives such as humate, peat, polymers, and clay minerals. An example is nanoscale preparation of urea and ammonium salts by emulsification followed by shearing to nanoscale.
>
> (2) Nanoscale additives: Nanomaterials are added to a macroscale or bulk input. In this case, the nanomaterials act as either a fertilizer (i.e., nutrient source) or supplement (e.g., water retention, biostimulant, plant protection). The primary rationale is that the additives enhance the uptake of nutrients and/or water and might impart pest resistance. An example is NPK fertilizer containing nanocarbons.
>
> (3) Nanoscale coatings or hosts: Nano-thin films or nanoscale pores in host materials encapsulate fertilizers to control the release of the inputs (e.g., polymers, clays). However, these particles can vary in their chemical composition, surface area, and charge dynamics. Nanocomposite structures might improve the thermal stability and mechanical properties of bulk material, adsorb nutrients to retain and release nutrients and water, or placed within the interlayer clay spacing to prevent decomposition from microbes, heat, and light. An example includes zeolite added to a composite fertilizer.

We can also conceptualize nanofertilizers by their composition according to Marchiol et al. (2020). For example, metallic nanomaterials encompass micronutrient nanofertilizers containing copper, iron, manganese, molybdenum, or zinc. In contrast, ceramic nanomaterials include calcium, magnesium, and/or phosphate minerals as well zeolites loaded with nutrients. Lastly, polymeric nanomaterials fall within a third category, which include carbon nanotubes, chitosan fertilizers, or carbon containing macronutrients.

Agronomic and environmental impacts

The impact of nanofertilizers on agronomic and environmental outcomes is poorly understood, and a systematic understanding of the mechanisms is needed (White & Gardea-Torresdey, 2018). Kah et al. (2018) performed a meta-analysis of 29 papers and reported positive effects on average for germination, plant growth, or yield for nanoscale macronutrients, micronutrients, and macronutrient carriers. However, the authors stated issues with low sample size, pervasive lack of fertilizer use efficiency data, absence of cereal crop studies, and little representation of field scale experiments. In another synthesis paper, only nine of the 126 articles that Raimondi et al. (2021) reviewed for smart fertilizers examined the impact of nanofertilizer on crop growth under field conditions. Of these, the majority were focused on micronutrient nanofertilizers, and the authors found that the studies reported mostly positive effects on various traits of interest, including yield, fruit set, soil properties, crop physiology, or water and nutrient use efficiency. In a third analysis, Nongbet et al. (2022) reviewed 11 studies on the effects of foliar application of nanofertilizers, and these authors reported enhanced yield, crop quality, growth, and disease suppression in all but one study, yet they also acknowledged the lack of studies investigating environmental impact (Nongbet et al., 2022). Lastly, Li et al. (2022) reviewed the ammonia mitigation efficiency of zeolite additives reported in seven papers and found reductions ranging from 25-50%, however only one of these studies was conducted in the field. To date, assessments of the environmental impacts of nanofertilizers under field conditions are still lacking; only one study investigated nitrous oxide emissions (Pereira et al., 2015) and two monitored nitrate movement by depth (Alimohammadi et al., 2020; Pohshna & Mailapalli, 2022). While Hofmann et al. (2020) recognized the potential benefits of nano-carriers and nanoscale fertilizers (both macronutrients and micronutrients) for plant growth (as recently explored in a special issue by White & Gardea-Torresdey, 2021), field trial research is needed before the technology can be considered ready for commercialization based on the scientific evidence of its performance.

Limitations and uncertainties

Depending on the nutrient, there may also be an apparent contradiction with nanofertilizers in which the purported greater surface area, faster dissolution, and higher saturation solubility might lead to greater reactivity, decrease nutrient use efficiency, and exacerbate environmental losses (Mastronardi et al., 2015). Considering the lack of field trials, the behavior of nanfertilizers beyond petri dishes and in the soil environment is poorly understood (Marchiol et al., 2020). While foliar application of nanofertilizers may potentially aid nutrient assimulation, we still lack an understanding of factors that regulate leaf and cellular uptake mechanisms particular in light of the heterogeneity of plant tissues and the barriers that nanoparticles must cross (Husted et al., 2023). Furthermore, Mastronardi et al. (2015) states that many studies lack evidence on greater nutrient uptake and differences in dissolution kinetics, and do not always identify the mechanisms for the positive effects on plant growth, while Husted et al. (2023) point to the lack of experimental controls. More worrisome, but an opportunity for research and development, is the lack of functional nanoscale devices that release nutrients based on plant signals or in response to changing nutrient levels in the soil (Derosa et al., 2010). Not much is understood about the potential for bioaccumulation of many nanoscale particles in the food chain, and there is some evidence of detrimental impacts of nanoparticle accumulations in plants (Rico et al., 2011) and on the soil microbiome (Nogueira et al., 2012). Other potential barriers include the delivery at field scale, regulatory and safety concerns, and consumer acceptance (Hofmann et al., 2020). To overcome these constraints, researchers might look to the field of medicine and drug development and the studies on complex biosystems to develop solutions dependent on biocompatibility, biodegradability, and non-toxicity (Hofmann et al., 2020; Mastronardi et al., 2015)

Bioformulations

Definitions and modes of actions

Biofertilizers are defined as formulations that contain one or more strains of microorganisms that colonize the rhizosphere, rhizoplane, or root interior of a plant and enhance its nutrition by mobilizing or increasing nutrient availability in the soil. These formulations, referred to as bioformulations, are biological products that contain inocula, solid or liquid carriers, additives, and/or treatments. Bioformulations are increasingly the subject of commercial interests, ranging from the emergence of startup companies backed by venture capitalists to established fertilizer companies embarking on their own development or aquisition of smaller companies. Robust evaluation is urgently needed to quantify the effectiveness of bioformulations in this fast-growing industry.

Some researchers consider biofertilizers as a subcategory of the more general classification of plant growth promoting microorganisms because not all microorganisms that promote plant growth also increase nutrient availability (Mitter et al., 2021). Nevertheless, these terms are not mutually exclusive, and though the primary function of biofertilizers is to aid in the transformation and/or acquisition of plant-available nutrients, their activity may have plant growth promoting impacts as a secondary function (e.g., imparting abiotic stress tolerance). Biofertilizers–and plant growth promoting microorganisms more broadly–may also be considered a subcategory of biostimulants (du Jardin, 2015; Yakhin et al., 2017), which *"support a plant's natural processes independently of the biostimulant's nutrient content, including by improving nutrient availability, uptake or use efficiency, tolerance to abiotic stress, and consequent growth, development, quality, or yield."* Likewise, according to the European Biostimulants Industry Council, *"Plant biostimulants means a material which contains substance(s) and/or microorganisms whose function, when applied to plants or the rhizosphere, is to stimulate natural processes to enhance/benefit nutrient uptake, nutrient efficiency, tolerance to abiotic stress, and crop quality, independent of its nutrient content."* However, like biofertilizers, there is no globally accepted definition for regulatory or commercial purposes.

Biofertilizers can work to increase the availability of essential plant nutrients. General types of microorganisms include symbiotic and free-living nitrogen fixing bacteria, phosphorus solubilizing and mineralizing bacteria/fungi, potassium solubilizing bacteria/fungi, bacteria that oxidize sulfur, microorganisms that exude chelating agents or solubilize micronutrients, and mycorrhizal fungi (O'Callaghan et al., 2022). Other authors have reviewed biofertilizers extensively and in great detail (Mitter et al., 2021; O'Callaghan et al., 2022). These reviews discuss how bioformulation product development has largely moved away from single-strain inoculation in favor of microbial consortia to improve survival and function of the microorganisms and/or to provide synergism such between arbuscular mycorrhizae and nitrogen fixing bacteria. However, these microbial consortia may experience the same limitations that single-strain inocula face, including antagonistic interactions with resident microorganisms, failure to establish under a range of environmental and soil conditions, and lack of persistence with time (Menéndez & Paço, 2020). Therefore, Mitter et al. (2021)

propose strategies to screen, design inocula, and optimize formulations for commercial production.

In the selection and screening of microorganisms, technological developments have allowed for rebirth of culturing techniques (i.e., culturomics) to facilitate the growth of slow-growing or rarer microorganisms (Lagier et al., 2015, 2016). To extend this to plant and soil sciences, researchers have coupled culturomics with plant-tailored culture techniques that produce microorganisms on plant-based media instead of materials of animal origin (Sarhan et al., 2019). Biofertilizers can also include artificially selected microbiomes (Mitter et al., 2021). The selection of microbiomes through "top-down" approaches modifies an existing microbiome to perform certain functions through the manipulation of environmental conditions and ecological selection (Lawson et al., 2019). In contrast, "bottom-up" approaches start with the pre-selection of individual, functionally beneficial microorganisms to build artificial or engineered microbiomes (Lawson et al., 2019). This simplifies the complex interactions through a pre-selection process, which might start with keystone taxa (e.g., network analysis) followed by functional assessment. This approach utilizes culture-independent techniques that aim to artificially build microbial communities, such as the synthetic communities approach, by selecting microorganisms from core collections to recreate the structure and function but with less complexity (de Souza et al., 2019; Vorholt et al., 2017). In their perspective paper, Mitter et al., (2021) proposed that the selection of microbial assemblies be based on interactions between microorganisms, functional traits of interest, colonization capabilities, and with high functional redundancy to increase adaptability.

Translating the understanding of soil microbiome function to fertilizer product development remains a challenge, and the efficacy of inoculation can be hindered by soil and environmental factors (e.g., presence of antagonists; abiotic factors such as climate, nutrient content, pH, organic matter, moisture, etc.), plant related challenges (e.g., specificity or colonization), and poor ecological traits and tolerance (Mitter et al., 2021). Therefore, alternative inoculum strategies might be necessary. One strategy is biofilmed biofertilizers that contain multi-species microbial communities within a suitable environment to enhance the competitiveness with the resident community and tolerate biotic and abiotic stress in the soil (Turhan et al., 2019). In biofilms, microorganisms adhere to biotic or abiotic surfaces in a matrix of extracellular polymeric substances, and the microbes are chemically linked by quorum sensing within a matrix that provides structure and protection. A second strategy might be the addition of "prebiotics" that act as microbial substrates or signals to stimulate the beneficial plant-associated microbiota (Vassileva et al., 2020), such as root exudates (e.g., sugar and organic acids) or plant-derived secondary metabolites. While prebiotics can be introduced in the absence of inoculation to promote the microbial functions in the resident community, Mitter et al. (2021) propose to couple prebiotics with microbial inoculants to increase biofertilizer efficiency and colonization.

After the selection of microorganisms, the formulation and delivery methods must be optimized and scaled to maintain the viability of bioformulations during storage and application. Typically, bioformulations are either delivered with solid carriers (e.g., peat, rock, phosphate, charcoal, clay minerals, cellulose, or polymers) or as liquid formulations (e.g., water, oils, emulsions) (Mitter et al., 2021). Formulations can also include additives (e.g., methyl cellulose, starch, silica gel) to improve their physical, chemical, and nutritional properties. Both carrier types have disadvantages, including the loss of overall viability during rewetting of solid carriers or the reduction of metabolic activity and risk contamination with liquid carriers. Mitter et al. (2021) put forth two strategies for the commercialization of bioformulations, including polymeric gel encapsulation and fluid bed dryer methods. Polymeric hydrogels are synthetic or naturally occurring cross-linked polymer chains that provide an aqueous environment for encapsulated material and form a semi-permeable barrier across which certain molecules to diffuse, which can help overcome these limitations and deliver viable microorganisms (Gasperini et al., 2014). Used in pharmaceuticals and the food industry, the fluidized bed dryer technology suspends particles in an air stream like a fluid and then a coating material is sprayed through a nozzle, followed by drying (Schoebitz et al., 2013). Though improved carriers and drying methods may improve viability and extend shelf-life, both solutions may be costly (Mitter et al., 2021).

Agronomic and environmental impacts

Schütz et al. (2018) performed a meta-analysis on five categories of biofertilizer (including arbuscular mycorrhizal fungi, P solubilizers, N fixers, a combination of both P solubilization and N fixation) and reported that their impact on yield depended on environment and nutrient levels in the soil. Leggett et al. (2015) also reported positive impacts of inoculating maize with phosphorous-solubilizing fungus, but effects were small (1.8% increases) and variable with only 72% of replicated trials responding positively. In the review by Raimondi et al. (2021) on smart fertilizers, bioformulations made up only four of the 126 field-based studies. These authors report that (i) the results were inconclusive, (ii) the studies did not consider mass balance of nutrients, and (iii) were likely not a substitution for fertilization. For bioformulations, it is not uncommon for a strain to perform well in vitro but not in the field (Hart et al., 2018; Kaminsky et al., 2019), and there is a need for more research to improve their performance under field conditions (Compant et al., 2019). Furthermore, the literature on the environmental impacts of biofertilizers is scarce (O'Callaghan et al., 2022). Li et al. (2022) reviewed seven field-based papers on the impact of biofertilizers on the mitigation of ammonia losses, and these authors reported that ammonia volatilization decreased by 32-76%. Field studies investigating nitrous oxide emissions are rare (Gay et al., 2022; Shrestha et al., 2022; Tao et al., 2018; Xu et al., 2014) as well as those monitoring nitrate leaching (Sun et al., 2020; Xu et al., 2017) though the few papers available report neutral to positive impacts on the mitigation of losses.

Limitations and uncertainties

Standardized and universal testing protocols and evaluation guidelines can help examine the inconsistent impacts across crops, soils, and environments in moving along the lab to field pipeline. However, O'Callaghan et al. (2022) called for more rigorous field testing in response to the deficit of field studies. These authors also cautioned readers about the risks of publication bias, the overestimation of effect size, non-reporting of confidence intervals, and lack of reproducibility, which may hinder our understanding of the full scope of fertilizer performance and impact. Martínez-Hidalgo et al. (2019) and Mitter et al. (2021) stated additional challenges to commercialization, including the lack of recommendations, short shelf life of products and other logistical concerns, costs of scaling technologies, and the need to establish biosafety guidelines and understand risks to human health.

Novel enhanced efficiency fertilizers

Definitions and modes of actions

As discussed earlier, controlled release materials can be defined as nutrients mixed or coated with one or more materials or additives that exploit synergy and affect nutrient release. However, there is a great deal of overlap between controlled release fertilizers and nanofertilizers or bioformulations, and so the discussion here is limited to what has not been previously covered. More generally, traditional controlled-release fertilizers fall within this category, in which coating or matrices physically control the release of nutrients via organic or inorganic materials, hydrogels, hydrophobic matrices, or low solubility minerals. Likewise, stabilized forms of fertilizers, such as those treated with enzymatic inhibitors, may be placed under this broader category, in addition to other novel means to biochemically control the release of nutrients such as via biosensors or plant signals (Raimondi et al., 2021).

Physical control

Physical control release mechanisms can include reducing the solubility of fertilizer, increasing mechanical strength, and enhancing abrasion resistance (Raimondi et al., 2021). Coated fertilizers are an example of this, in which a low permeability film or matrix prevents physical contact between the fertilizer and soil to slow its release (Fu et al., 2018). Scientists have explored an assortment of different coating materials, but the industry has shifted to biodegradable materials over environmental concerns of the use of plastics micro or nano-scales that require time to degrade and release nutrients (Campos et al., 2015). Hydrogel materials, as discussed earlier, are a type of innovative technology with super absorbent properties that can either be coated onto fertilizers or prepared as a matrix (Skrzypczak et al., 2021). Hydrogels can be derived from naturally occurring sources or synthetic, and the most common polysaccharide materials include alginate, starch, cellulose, cyclodextrin, dextran, guar gum, pectin, chitosan, while acrylic acid or acrylamide are example of synthetic sources (Campos et al., 2015). Ultimately, formulations would respond to stimuli and release nutrients as a function of environmental changes (e.g., pH, T, salinity, humidity, light) (Skrzypczak et al., 2021).

Biochemical control

Biochemical control release mechanisms exploit biochemical response to delay nutrient release through the addition of biochemical sensors, enzyme inhibitors, or materials that alter their properties in response to major environmental factors (Raimondi et al., 2021). The addition of biochemical inhibitors, either homogenized within or coated on fertilizer granules, can temporarily slow nutrient transformations by inhibiting enzyme activities (Fu et al., 2018). Different types of urease and ammonia monooxygenase inhibitors exist on the market, but next generation inhibitors might include analogues with structural variations (cyclic groups, heteroatoms, and polarity) to impart better stability (Lam et al., 2022). Thinking beyond those targeting microbial activity, novel plant-oriented approaches on the horizon rely on the plant-microbe interactions in which microbes use chemotaxis (or signaling) in response to signaling molecules such as proteins, peptides, lipids, RNA, phytohormones, metabolites to attach to a root/form biofilm and aid in nutrient acquisition (Lam et al., 2022). Novel formulations might include signaling molecules incorporated into the coat of fertilizers and then can attract microbes in the rhizosphere to trigger nutrient release.

Another novel mechanism for controlled nutrient release is to embed biosensor or receptor molecules into the fertilizer coat to respond to plant signaling molecules and then release nutrients (Lam et al., 2022). Aptamers, for example, are single stranded synthetic oligonucleotides made using sequencing libraries that fold in unique shapes and bind to targets with high specificity, such as root exudates. These molecules interact with their targets through non-covalent interactions and shape complementarity, and they behave like biosensors to target root exudates or biomarkers which allow the fertilizer to “sense” plant signals to release. In addition to aptamers, antibodies and molecular imprinted polymers are also affinity ligands that fall within this category. The assumption is that these biosensors are indicators of plant nutrient needs. However, more work is needed to commercialize these products given that some aptamers may have partial binding to solids that may challenge measurements in solution due to interference, and the technology is also more costly for longer aptamers (Mastronardi et al., 2021).

Agronomic and environmental impacts

Controlled release or stablilized formulations make up the vast majority of field studies reviewed by Raimondi et al. (2021). Sixty-six of the 126 studies tested polymer-coated urea, while 18 were devoted to inhibitors. Previous literature has well documented the beneficial impacts of the traditional controlled release and stabilized sources of nitrogen on the reduction of environmental impacts and yield gains (Lam et al., 2022). However, it is not known what proportion of these studies include biodegradable polymers. Raimondi et al. (2021) noted that synthetic non-biodegradable materials had slower release rate than biodegradable and cellulose acetate-based ones. Only three field studies have been performed using biodegradable polymers (Li et al., 2017; Santos et al., 2020, 2021), all of which reported reductions in ammonia volatilization.

Limitations and uncertainties

Many of the limitations that we have previously discussed also pertain to controlled release or stabilized fertilizers. For instance, the commercialization of new compound products may be challenged by the risk for accumulation and toxicity, poor or weak formulations, chemical instability, and unpredictable field performance (Lam et al., 2022; Raimondi et al., 2021).

Novel decision support products

For the last two decades, the public and private sectors have promoted 4R Nutrient Stewardship or similar concepts as the overarching method for best fertilizer management practices. Its four pillars include applying the right nutrient source at the right rate, right time, and right place (Fixen, 2020). Fundamentally, 4R nutrient management is not a one-size-fits all approach, and the selection of fertilizer management practices is based on site conditions that may vary spatially and temporally. In practice, fertilizer management consists of adaptable suites of strategies; though seemingly intuitive, this nimble aspect of nutrient management convolutes efforts to isolate the impacts of specific fertilizer management practices on crop production or environmental outcomes (Maaz et al., 2021). Improving nutrient use efficiency is a central concept for enhanced efficiency fertilizer products (Hatfield & Venterea, 2014; Lam et al., 2022; Snyder et al., 2009), yet teasing out which enhanced efficiency fertilizer products work where, when, and at which rate is not always straightforward. Previous research suggests that certain fertilizer sources may be more effective for a given combination of rate, timing, and placement (Janke et al., 2020) while crop yield and environmental outcomes likely depend upon the type of fertilizer, cropping system, and biophysical conditions (Li et al., 2019). To further complicate matters, the addition of enhanced efficiency fertilizers may even lead to unintended consequences, such as decreasing nitrous oxide emissions at the expense of increasing ammonia volatilization in some years (Drury et al., 2017) but not others (Woodley et al., 2020) leading to uncertainty in their overall environmental impacts. Importantly, if crop nutrient uptake is not enhanced, the reduction in one loss pathway might increase the losses through other pathways. Therefore, we must have a better understanding of the performance of enhanced efficiency fertilizers particularly within the context of nutrient cycling dynamics and crop nutrient demand (Verburg et al., 2022).

Fertilizer recommendations aim to optimize the application rates of fertilizers to meet but not exceed the plant nutritional demand. As such, fertilizer recommendations theoretically maximize production or quality goals while minimizing environmental impacts. However, approaches may differ depending upon the nutrient of interest. For instance, nitrate is a highly mobile nutrient in soil that moves through mass flow and has low retention in soils dominated by negatively charged colloids. Therefore, researchers have historically based nitrogen recommendations on the expected yield of the crop, or in other words, by first determining the nitrogen demand of the crop at a specific yield goal (Morris et al., 2018). Developed by Stanford (1973), this approach derives a fertilizer recommendation by subtracting out the amount of nitrogen that can be supplied by the soil from the yield-based crop requirement, which is then adjusted by the crop's uptake efficiency (e.g., the fraction of nitrogen that the crop recovered from an application of nutrients).

In contrast to nitrogen, phosphorus is relatively immobile in soil due to its high reactivity with soil colloidal surface (i.e., chemisorption/ligand exchange) and its precipitation reactions, and therefore diffusion dynamics govern plant uptake. Phosphorus recommendations are generally based on measurement of plant-available phosphorus, and application rates are empirically determined by the amount of phosphorus needed to bring soil test values up to critical phosphorus levels (Gagnon et al., 2020). Given that phosphorus sorption and precipitation can vary greatly among different soil types, researchers may develop buffer coefficients to determine the amount of fertilizer needed to meet the critical phosphorus concentration for a given crop (Wang et al., 2000).

While these generalized approaches might be logical and simplistic, in practice, deriving nutrient recommendations is quite complicated which has been a point of concern for decades (Dobermann & Cassman, 2002). As stated in Morris et al. (2018), "*logic is sometimes referred to as 'a systematic method of coming to the wrong conclusion with confidence' (perhaps Edward A. Murphy).*" Fertilizer recommendations are often plagued by lack of reproducibility when attempting to extrapolate results beyond the conditions for which they were calibrated. A lack of nutrient response, for instance, may be due to factors such as high residual nutrient levels, poorly predicted nutrient mineralization and release dynamics, variable soil properties and climate conditions, differences in plant growth, and the complexity of plant-soil-microbial interactions (Morris et al., 2018). Another layer of complexity that challenges the generalizability and reproducibility of nutrient recommendations is that optimal application rates may be influenced by the timing, source, and placement of fertilizer in addition to other management factors (Morris et al., 2018).

One way forward is to fine-tune generalized recommendations on a field or subfield level through adaptive management (Morris et al., 2018). This might be done by farmers implementing their own on-farm strip trial, followed by the evaluation of the fertilizer response, and then adjusting fertilizer practices. However, making sense of the variability in yield responses may depend on the collection of critical data related to plant, soil, climate, and management factors, followed by its analysis with advanced statistical techniques. Likely, the necessary data needs overlap with the needs for proper environmental evaluation as previously discussed. Additional measurements for soil organic matter and soil health parameters can also be collected (Kladivko et al., 2014), which can help tease out the variability of nutrient responses across space and time.

Digital tools also allow us to understand the variability in plant growth over large spatial extent with increasing resolution, and therefore enabling site-specific management of fertilizers. For instance, crop sensor technology may provide rapid, spatially-explicit assessments of yield potential and/or nutrient responses that can better inform in-season nitrogen management (Basso et al., 2019; Franzen et al., 2016). Likewise, soil spectral techniques may help predict soil properties in the field, increase the reproducibility of soil analyses, and decrease time and costs associated with analyses (Asrat et al., 2023). Nevertheless, this technology suffers from the inherent limitations of traditional approaches: sensors still must be calibrated to specific field conditions, nutrient uptake efficiencies are poorly understood, and weather and soil data may be needed to improve predictions. Ultimately, models are only as good as the data used to calibrate them, meaning that field trials and field data are needed to get more accurate decision support from digital tools. With advancements in weather forecasting, nutrient management tools that incorporate weather data, nutrient loss models, and short-term forecasting information to overcome these limitations and help identify high-risk environmental conditions that reduce nutrient use efficiency (Easton et al., 2017).

Novel digital decision tools can help predict and synchronize the rate, timing, and duration of nutrient release with plant demand; and the development of digital crop nutrient solutions is a major focus of the new responsible plant nutrition paradigm (Dobermann et al., 2022a). However, historically, the adoption of decision support tools is low in the agricultural sector (Rose et al., 2016), and these tools have largely not exploited the major advancements in data, research, and models (Antle et al., 2017). In response, agricultural system simulation models have worked to broaden their scopes and scales to evolve from cropping system models to "next-generation" agroecosystem models (Holzworth et al., 2014). Delgado et al. (2019) argues that researchers are in the position to leverage digital agricultural tools, sensor networks, large regional databases, and artificial intelligence algorithms to improve data classifications and predictions to aid decisions across space and time. The application of supervised learning techniques holds potential to improve nutrient management tools. Recent research demonstrates that artificial intelligence can provide crucial insights into the soil, nutrient, and environmental interactions and indicators that lead to variability in crop nutrient responses (Zingore et al., 2022), nutrient status (Khan et al., 2022; Siva, 2019), and yields (Timsina et al., 2021, 2022) that beleaguer nutrient recommendations. It is also conceivable that supervised learning algorithms may help tailor product specifications of compound fertilizers for specific crops grown in specific soil environments, and thus achieve better performance and overall nutrient use efficiency (Figure 4).

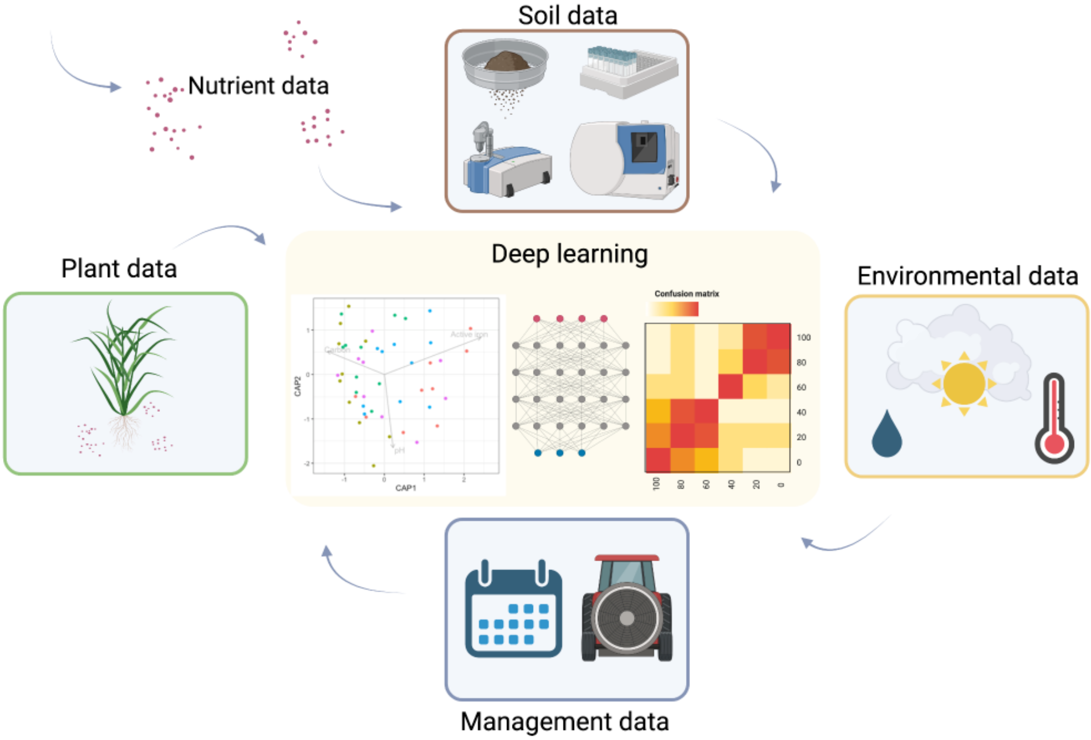

Figure 4. Novel "smart products" may leverage nutrient, soil, plant, management, and environmental data to provide tailored nutrient recommendations. Created in BioRender.

Other nutrient challenges and solutions

Nutrient shortages

While most of this white paper has focused on the excess supply of nutrients, underrepresented regions with vast cropland still lack sufficient available nutrients for food security (Ciceri & Allanore, 2019). Furthermore, over 90% of projected increases in global food production must come from higher yields and greater cropping intensity due to limited land available for agricultural expansion (FAO, 2009). Soil degradation—driven by nutrient mining due to inadequate nutrient additions—is a cause of food insecurity and malnutrition (Lal, 2009). Areas with inadequate nutrients face major challenges while increasing fertilizer to improve productivity but minimize environmental impacts. Minimizing nutrient surpluses is critical given that increasing nitrogen fertilizer rates from 50 to 150 kg ha^{-1} season^{-1} is projected to increase N_2O emissions in the tropics by 30% (Huddell et al., 2020). Research strategies must be identified to sustainably increase fertilizer use in underserved areas overcoming historical trajectories (Zhang et al., 2015), but each of these regions requires specific interventions, including innovations that are tailored to their specific environment and cropping systems (Vanlauwe & Dobermann, 2020).

Breeding approaches to enhanced efficiency

In addition to the enhanced fertilizer products, other solutions to improve nutrient use efficiency include crop breeding strategies to provide alternate means of delivering nitrogen to crops or modifying the nitrogen cycle. For instance, a plethora of research has been devoted to introducing biological nitrogen fixation symbiosis into non-legume crops (Wen et al., 2021) or even through the direct bioengineering of nitrogen fixing plants (Pankievicz et al., 2019). Recent advancements have also identified root exudates that act as nitrification inhibitors or signaling compounds to facilitate nitrogen acquisition (Coskun et al., 2017). Such crop genotype-microbe interactions may play an increasingly important role in crop breeding (Udvardi et al., 2021), which may help select or engineer plants with these features or specific plant traits to increase nutrient use and utilization efficiency (York et al., 2022).

Novel production technologies

Novel production processes can also help reduce environmental impacts of fertilizer production. One technology is referred to as “green ammonia production.” This process produces ammonia that is renewable and decarbonized by using dinitrogen from the atmosphere and hydrogen from electrolysis (Faria, 2021). These electrochemical systems can be small and even provide a means for on-site fertilizer production powered by wind or solar energy systems, though the technology is still in the early stage (MacFarlane et al., 2020). Other renewable energy technologies include producing fertilizers, such as ammonium sulfate, from nutrients recovered from waste streams or ash as part of a circular economy via electrodialysis (Guo et al., 2021) or air-stripping (Kar et al., 2023). Life cycle analyses indicate that circular economy technologies would help reduce greenhouse gas emissions and energy use (Kar et al., 2023). While decarbonization is a major outcome of this work, questions regarding the efficiency of its fertilizer products in absence of novel formulations remain.

A path forward

Nutrient management is critical for both future food security and protecting environmental resources. Recent events in Sri Lanka demonstrate the vulnerability of a nation’s food production to cutting off its supply to fertilizer (Weerahewa et al., 2021), emphasizing the need for solutions that protect both agronomic and environmental interests. Given the complexity, efforts to solve nutrient management problems ought to involve more open innovation, particularly in the pre-competitive research space and through more public-private collaboration. Here, we have reviewed (1) general approaches to facilitate and standardized collaborative innovation and (2) novel technologies for areas of potential investment. Through this process, we identified the need for more robust agronomic and environmental evaluation of fertilizer products and practices, which will likely involve coordinated efforts that collect and harmonize large datasets across space and time. These efforts will require teams to explicitly develop their minimum data standards, data dictionaries, common standardized protocols, experimental controls, experimental designs, and statistical approaches.

Investments in the pre-development of novel fertilizer products and tools are also paramount to this process, in which the evaluation of environmental impacts can occur along the laboratory to field pipeline. We reviewed novel fertilizers technology including nanofertilizers, bioformulations, and next generation enhanced efficiency fertilizers.

Categorization of products is often desired particularly from a regulatory and standardization perspective, however, there is often overlap among these fertilizer categories. Some of the more innovative solutions involve cross cutting technologies, such as bionanofertilizers (e.g., aptamers, root cell binding sites) (Mastronardi et al., 2021) and the bioactivation of nanocomposites (Guimarães et al., 2018; Klaic et al., 2018). This might mean that we need to balance the needs for product standardization for quality assurance and regulation while maintaining flexibility for discovering or combining novel modes of actions. We must also think about the performance of enhanced fertilizer products within the context of plant, soil, and climate factors; and this may necessitate the use of decision support tools to optimize fertilization holistically. However, nutrient management tools have largely not exploited the major advancements in data science, presenting an opportunity for further research and development.

We can look towards the achievements gained through more open innovation in other sectors. A common theme in the novel fertilizer literature is that research in pharmaceutical and food sectors might serve as inspiration for fertilizer product development (Mastronardi et al., 2015; Mitter et al., 2021). Similarly, medical and pharmaceutical researchers have also called for open innovation to develop products for the betterment of human health (Yeung et al., 2021). To spur innovation, the Foundation for Food & Agricultural Research Efficient Fertilizer Consortium has developed the following research themes and steps to promote more open innovative research:

- Theme 1: Establish common protocols for field trials to evaluate the agronomic performance and environmental impact of fertilizers.
- Theme 2: Engage a global network of independent research locations to implement the field trials.
- Theme 3: Conduct evaluation of standardized results in meta-analyses to improve emissions factors and computational model representation of fertilizer emissions.
- Theme 4: Invest in pre-competitive research on novel fertilizer types and/or modes of action.

These steps will help the consortium achieve its goals of increasing standardized testing of fertilizer products, expanding broader access to efficient fertilizer products, ensuring food security, and reducing the environmental impacts from fertilizer use.

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Supplemental 1:

Patent search results of innovations in biofertilizers

Supplemental 2:

Patent search results of innovations in nanofertilizers