SCIENTIFIC PANEL
ON RESPONSIBLE PLANT NUTRITION

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Novel fertilizers and how they work

by the Scientific Panel on Responsible Plant Nutrition

Content

Key points

Nutrient recovery efficiency for conventional fertilizers is often below 60% for nitrogen due to losses from leaching and volatilization and even lower for phosphorus and micronutrients due to strong soil retention.

There is significant potential to enhance efficiency through innovative fertilizers and their applications. These so-called novel fertilizers are advanced formulations designed to improve nutrient use efficiency and crop performance, and reduce environmental impacts. As agriculture focuses on sustainability, developing these fertilizers is critical for simultaneously achieving productivity and environmental outcomes.

Enhanced-efficiency technologies (Fig. 1) include inhibitor-treated fertilizers, slow- and controlled-release formulations, microbial coatings, nanofertilizers, and carrier technologies (e.g., graphene, layered double hydroxides, and metal-organic frameworks). While promising, many innovations face challenges in cost, scalability, and long-term environmental and agronomic performance.

Adopting novel fertilizers is often limited by higher costs, inconsistent agronomic benefits, logistical issues, manufacturing complexity, and regulatory hurdles. Additionally, many innovations lack robust field testing to demonstrate clear economic and environmental advantages for farmers. To assess new fertilizer formulations, four aspects should be documented: (1) mode of action, (2) agronomic and environmental efficiency, (3) ease of handling and logistics, and (4) cost, complexity, and environmental footprint of manufacturing. Rigorous testing under field conditions and standardized experimental protocols are crucial for validation.

Governments, industries, researchers, and farmers must collaborate to innovate, evaluate, and adopt sustainable fertilizer technologies. Policies, incentives, and streamlined regulatory frameworks are necessary to promote the development and wider use. Success would involve fertilizers with lower greenhouse gas emissions, improved efficiency, better agronomic performance, and a reduced environmental footprint.

SCIENTIFIC PANEL
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Novel fertilizers and their modes of action

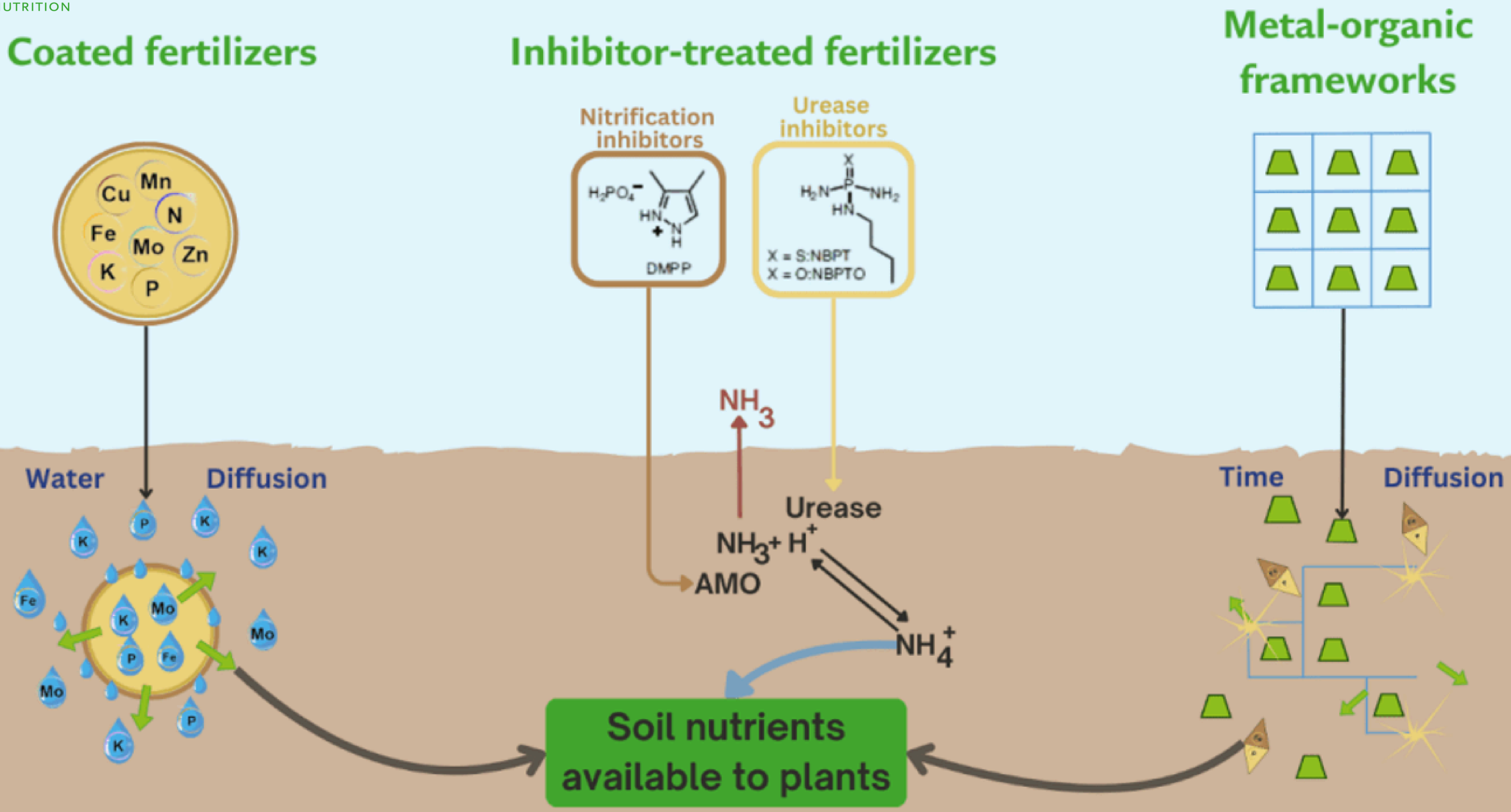


Figure 1. Examples of enhanced-efficiency fertilizer technologies and how they work in the field.

What is the issue?

Novel fertilizers are formulations that include coatings, carriers, inhibitors, microorganisms, nanomaterials, etc., specifically formulated to improve nutrient use efficiency (NuUE), enhance crop performance in terms of yield or quality, and/or reduce environmental impacts.

These formulations aim to improve the supply of a wide range of essential or beneficial elements for plant growth. They are based on different mechanisms of action and are used for different purposes. With the global push to improve the sustainability of agricultural production practices, there has been a marked increase in the number of publications, patents, and products related to novel fertilizer technologies. Understanding the modes of action of novel fertilizers, developing appropriate protocols for their assessment, and clearly documenting performance outcomes with appropriate metrics is essential to provide informed decisions to end users of these products.

With the increased number and type of novel fertilizers in the marketplace, it becomes imperative to have clear definitions of product categories, their efficacies, and how they can best be assessed to support claims. Here, we provide a review of the main modes of action needed to improve the efficiency of nutrient use, types of novel fertilizers, and robust methods to assess performance. We focus on inorganic fertilizers predominantly of synthetic or mineral origin, and do not consider purely organic fertilizers, microbial products, or other biostimulants.

Efficiency of nutrient use in agriculture

Nutrient use efficiency by crops can be defined and measured in many ways. Agronomic efficiency (AE) defines the crop yield increase per unit fertilizer applied. For farmers, AE is a very relevant measure because it accounts for both the efficiency of nutrient uptake from fertilizer and its conversion into harvested product. To compare the efficiency of adding a specific fertilizer, product, or application method across different crops and environments, the fertilizer recovery efficiency (RE) is the preferred measure.

This is calculated as the increase in nutrients taken up in above-ground crop biomass per unit nutrient applied relative to an unfertilized control. Field studies are preferred for quantifying fertilizer AE and RE because the uptake efficiency of fertilizer nutrients applied to soil or leaves varies according to nutrient, application method and placement, timing, application rate, soil and crop type, and environmental conditions. Interpretation of both AE and RE values needs care due to these confounding factors. Additional crop indicators are needed to understand the mode of action of novel fertilizers, particularly nutrient uptake, translocation, distribution, and redistribution efficiency in the plant.

Nitrogen (N) is the macronutrient most readily lost from the root zone by leaching, runoff, or atmospheric losses. Leaching losses of N are high because no matter which form of N fertilizer is added to the soil, chemical, microbial, and enzymatic processes convert the added N into forms that can be lost. Microbial and enzymatic processes in soil convert added N into ammonium (NH_4^+) or nitrate (NO_3^-). Nitrate, as it is anionic, is not retained strongly in soil since colloidal particle surfaces are generally net negatively charged. Ammonia (NH_3) is produced by chemical and enzymatic processes from urea and ammonium-based fertilizers and is liable to loss to the atmosphere (volatilization). Furthermore, microorganisms may convert NO_3^- to other gaseous forms (such as N_2 and nitrous oxide, N_2O) easily lost to the atmosphere. These gaseous forms of N are generated depending on the form of N fertilizer added and the present soil conditions causing microbial or enzymatic transformation of N from one species to another.

As a consequence of N transformation and loss, the efficiency of crop acquisition of fertilizer N (RE) measured in field experiments varies from 10%-75%, with a global average of around 50%. Both more precise agronomic practices and fertilizer design aim to increase N-use efficiency. The general goal is to decrease the movement of N in soil (by controlling nutrient release or reducing conversion to nitrate) or decrease its conversion to gaseous forms such as ammonia (NH_3), nitrous oxide (N_2O) and other N-containing gases).

Innovations in N fertilizer design often focus on slow-release or controlled release formulations, but these two options should not be confused. A slow-release fertilizer is defined as a “fertilizer, of which, by hydrolysis and/or by biodegradation and/or by limited solubility, the nutrients available to plants are spread over a period of time, when compared to a “reference soluble” product”. A controlled release fertilizer is defined as a “fertilizer in which nutrient release is controlled, meeting the stated release rate of nutrient and the stated release time at a specified temperature”. This controlled rate of nutrient release is achieved by modifying readily available nutrient forms with recognized physical mechanisms such as coatings, occlusions, or other similar means. Both aim to achieve greater synchrony between nutrient release from fertilizer and crop nutrient demand (Fig. 2), thereby reducing losses and increasing the recovery efficiency.

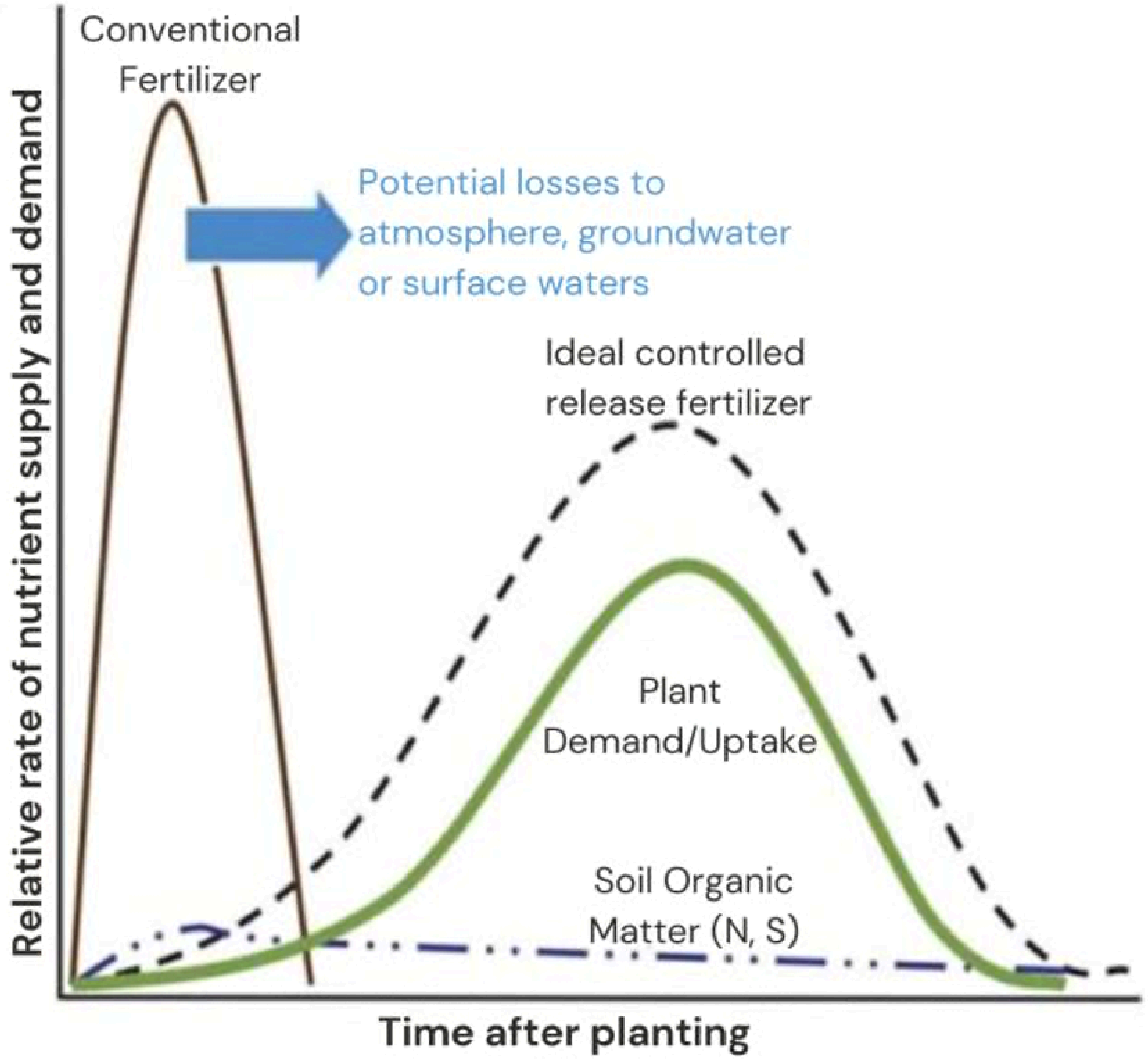


Figure 2. *Relative rates of crop demand for a nutrient (e.g., nitrogen) and supply from various sources. Controlled release fertilizers aim to delay nutrient release to achieve greater synchrony with crop nutrient demand. Source: adapted from Lam et al. 2024.*

Phosphorus is mainly added to soil as anionic ortho- or polyphosphates. Unlike nitrate, phosphate ions react strongly with soil cations such as aluminum (Al), iron (Fe), calcium (Ca), and magnesium (Mg) forming poorly soluble precipitates or strongly bound surface complexes. Losses to the atmosphere are negligible and losses to leaching or surface runoff are also relatively small in most soils. The crop recovery efficiency of fertilizer P is low in the year of application, generally 3%-35%. However, the fertilizer P strongly retained in the soil is not totally unavailable to crops. Over time, crops can access a portion of the retained P, often called "legacy P". By continuously applying P to a P-deficient soil, the RE of applied P rises and can exceed 90% in soils with large stocks of legacy P.

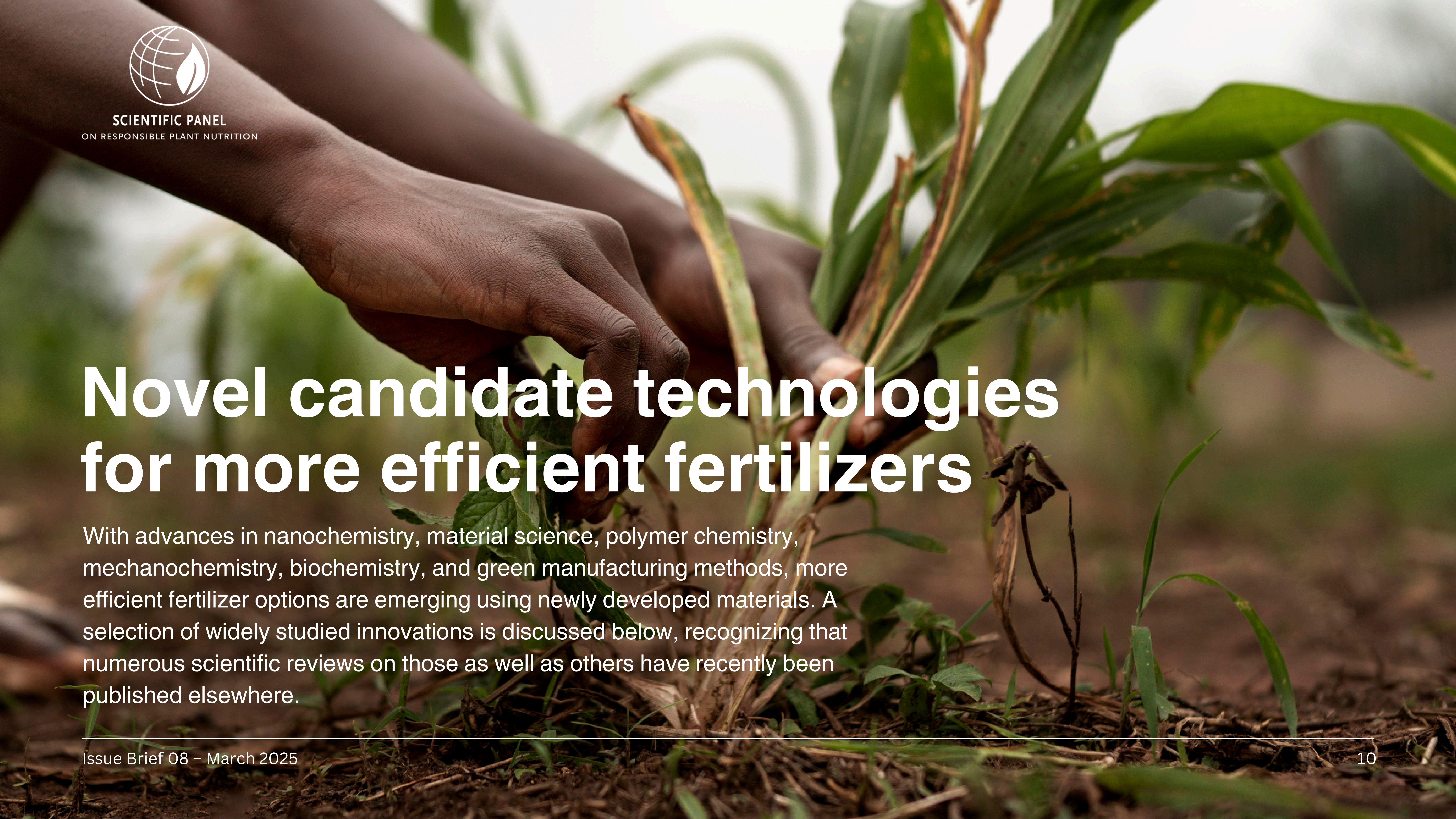
On soils deficient in P, products aiming to increase P fertilizer use efficiency should increase the soil mobility of applied P. On soils with a history of P fertilizer application that exceeds crop removal, the goal should be to improve plant access to legacy P to attain a new state where RE is high, while the level of stored P in soil is reduced. In practice, this involves fertilizing at a rate slightly below crop removal for several years before reverting to replacement rates. New chemical or microbial products that liberate some of this legacy P for crop uptake should be developed for these soils.

The efficiency of K fertilizer use has been less well studied, but generally, the RE ranges from 30%-50% based on crop nutrient uptake data. Values of up to 80% have been reported using an isotope-labeling technique under glasshouse conditions.

Relatively few data exist on the recovery efficiency of secondary (e.g. Ca, Mg) and micronutrient fertilizers. In the year of application, the RE may vary widely, particularly depending on the fertilizer form and whether it is soil- or foliar-applied. For example, the micronutrient cations copper (Cu), manganese (Mn), iron (Fe), and zinc (Zn) have particularly low RE values due to their very strong retention by soil, whereas foliar application directly to leaves may result in much higher RE. However, as for P fertilizers, there is a continuing residual agronomic effect of soil-applied micronutrients where annual applications in excess of crop demand may not be necessary. Hence, to increase fertilizer RE for these nutrients, novel micronutrient fertilizers should focus on increasing mobility in soil or applying nutrients directly to foliage in formulations that ensure effective uptake and/or movement throughout the plant.

Foliar fertilization may supplement soil-based plant nutrition by bypassing adverse soil processes. However, its implementation requires good penetration of mineral elements through leaf barriers and effective nutrient translocation. Since the effects of foliar fertilizers are short-lived and only small quantities of nutrients can be applied to leaves, repeated applications are often necessary to maintain nutrient levels. Also, applying foliar fertilizers in high concentrations or under hot, sunny conditions can cause leaf burn or damage. Moreover, foliar application may not be effective during earlier growth stages, when the canopy is not closed. Some nutrient runoff from foliage may also occur, particularly under high-rainfall conditions.

Given that the RE of many nutrients is generally low in the year of application, there is considerable scope to increase fertilizer use efficiency through new technologies to create enhanced efficiency fertilizers (EEFs). Here we summarize major technologies and recent developments in innovations to produce novel fertilizers.



Novel candidate technologies for more efficient fertilizers

With advances in nanochemistry, material science, polymer chemistry, mechanochemistry, biochemistry, and green manufacturing methods, more efficient fertilizer options are emerging using newly developed materials. A selection of widely studied innovations is discussed below, recognizing that numerous scientific reviews on those as well as others have recently been published elsewhere.

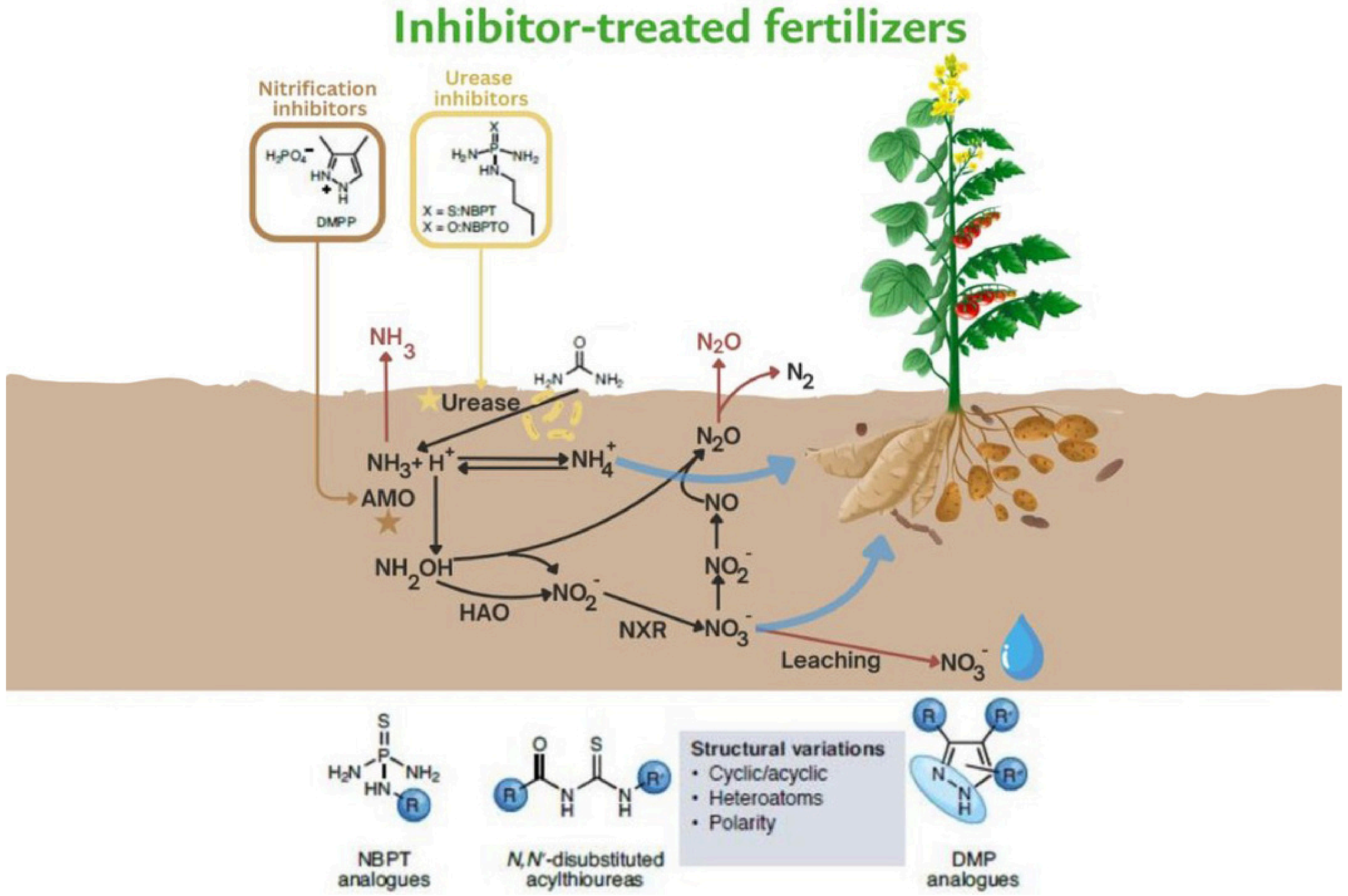


***Figure 3**. Current and next-generation chemical inhibitors. Processes targeted by chemical inhibitors are indicated by stars (yellow for urease inhibitors with NBPT as an example; blue for nitrification inhibitors with DMPP as an example). HAO - hydroxylamine oxidoreductase; NXR - nitrite oxidoreductase. Structural modifications of current urease and nitrification inhibitors may improve their efficiencies under various agricultural settings. Source: adapted from Lam et al. 2022.*

Inhibitor-treated fertilizers

This group of fertilizers, sometimes also called stabilized fertilizers, is not new technology per se, but represents the most established and commercially available type of advanced fertilizer formulation designed to increase N use efficiency. Inhibitor technology for N focuses on slowing the conversion of urea to ammonium using urease inhibitors and/or ammonium to nitrate using nitrification inhibitors (Fig. 3).

Nitrification and urease inhibitors were discovered more than 60 years ago and many products on the market are based on a few key active ingredients. NBPT (N-(n-butyl) thiophosphoric triamide) and 2-NPT (N-(2-nitrophenyl) phosphoric triamide) are commonly used urease inhibitors. Dicyandiamide (DCD), nitrapyrin, and 3,4-dimethylpyrazole phosphate (DMPP) are the most common nitrification inhibitors. New inhibitors have entered the market in the last decade e.g., DMPSA and pronitridine, a reaction product of urea with ammonium hydroxide, DCD, and formaldehyde[1]. However, this is mainly aimed for use with liquid urea-ammonium nitrate (UAN) or anhydrous ammonia.
Generally speaking, chemical N inhibitors have well-known modes of action and are particularly useful options for mitigating ammonia volatilization losses and greenhouse gas emissions as nitrous oxide. Studies on using urease and nitrification inhibitors in combination have shown potential for large reductions in gaseous N losses (30-75%), whereas increases in crop yield (1-9%) and N use efficiency (8-15%) are modest. Several compounds are being investigated for their ability to inhibit nitrification and it is likely that other new inhibitors will appear on the commercial market soon. It will be important to ensure that any new chemistry in this area does not pose any threats to soil quality or food safety.

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[1] Formaldehyde has been identified as a potential health risk, which is still undergoing further risk evaluation, https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/risk-evaluation-formaldehyde

Coatings

Coatings are generally used with highly soluble granular fertilizers to control the release of nutrients from the granule (Fig. 4) and minimize losses of nutrients from soil to the atmosphere (N), to leaching or runoff (N, P and S).

Like inhibitor technologies, fertilizer coatings are not by themselves novel as they have been researched for many decades. Coatings can be composed of various materials including nutrients or soil amendments (e.g., sulfur, gypsum, lime), synthetic chemicals (e.g., asphalt, thermoplastics, polyurethanes, resins, polymers), natural organic materials (e.g., waxes, oils, biochar, bio-based polymers, hydrogels), or microbial inoculants (e.g., bacteria, fungi).

Manufacturers often favour coating technologies since the underlying manufacturing of the base fertilizer products does not require any changes. Hence, the final fertilizer formulation can be more flexible by adding other nutrients, biostimulants or microorganisms to the base product. In this way, coating can be decentralized closer to the point of use, reducing risks of coating degradation in transport. Key requirements for commercialization of new coating technologies are: i) low cost for the coating material; ii) cost-efficient and scalable coating technology; iii) biodegradability in soil; iv) nutrient release timed to synchronize with crop demand; v) temperature-controlled release, and vi) suitable granule physical quality and stability (e.g. no cracks during processing, transport, or application).

Due to concerns for plastic pollution of soils when recalcitrant compounds are used for polymer-coated fertilizers, innovations in fertilizer coatings (Fig. 5) have recently focused more on biologically based polymers, hydrogel coating materials, stimuli-responsive coatings, or materials with greater degradability in soil.

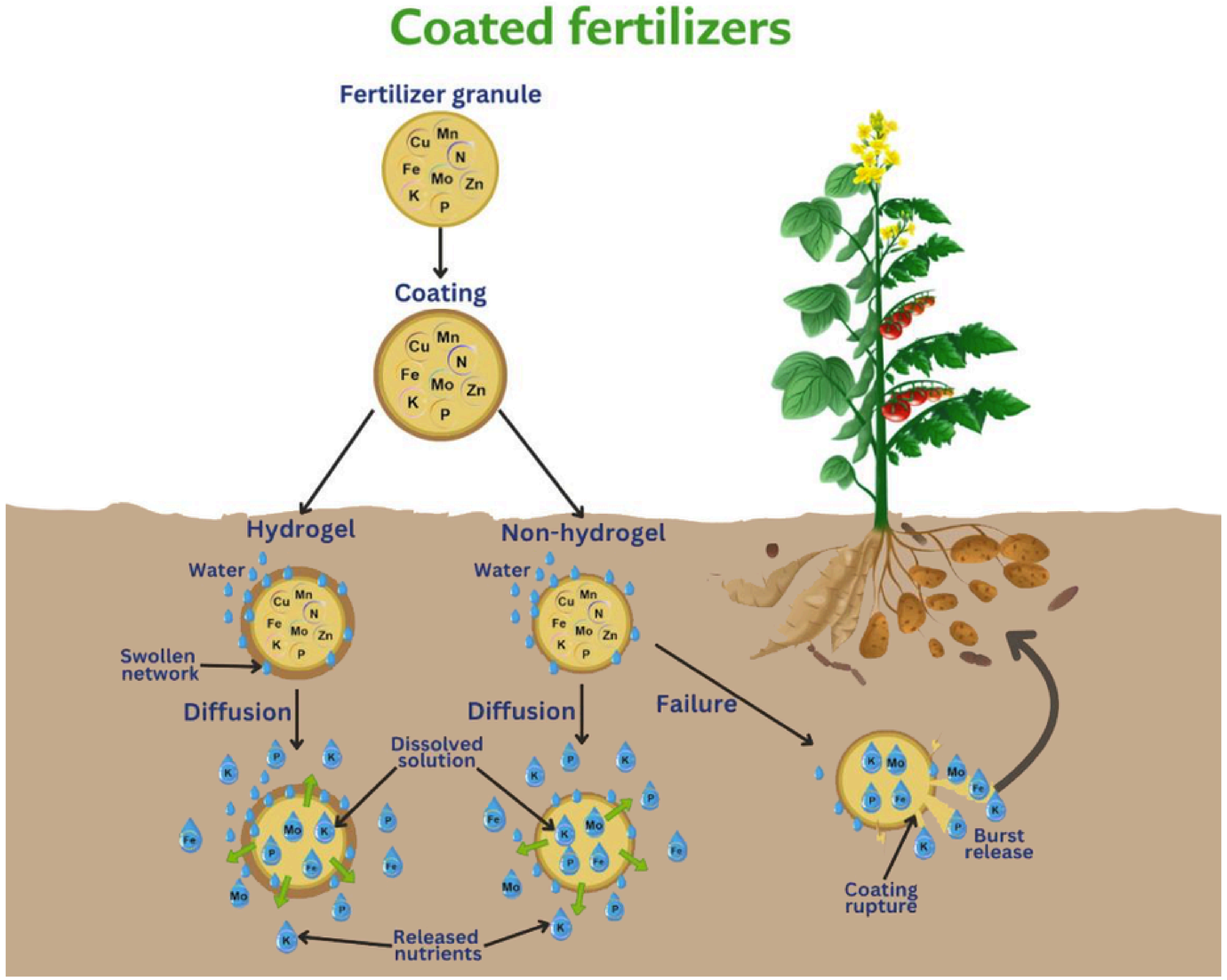
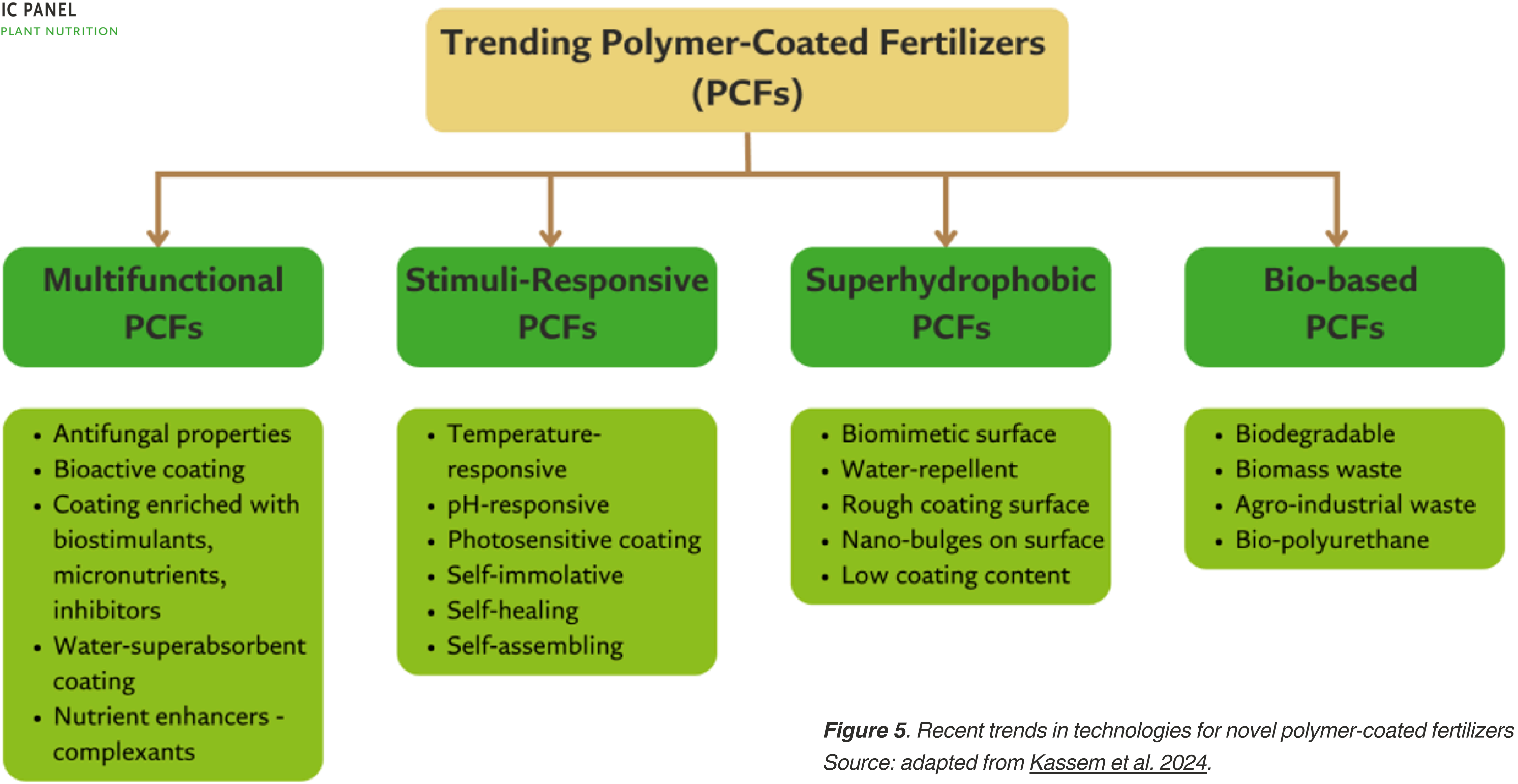


Figure 4*. Mechanisms of nutrient release from coated soluble fertilizers.*
Source: adapted from Kassem et al. 2024.



Trending Polymer-Coated Fertilizers (PCFs)

Multifunctional PCFs

- Antifungal properties
- Bioactive coating
- Coating enriched with biostimulants, micronutrients, inhibitors
- Water-superabsorbent coating
- Nutrient enhancers - complexants

Stimuli-Responsive PCFs

- Temperature-responsive
- pH-responsive
- Photosensitive coating
- Self-immolative
- Self-healing
- Self-assembling

Superhydrophobic PCFs

- Biomimetic surface
- Water-repellent
- Rough coating surface
- Nano-bulges on surface
- Low coating content

Bio-based PCFs

- Biodegradable
- Biomass waste
- Agro-industrial waste
- Bio-polyurethane

***Figure 5**. Recent trends in technologies for novel polymer-coated fertilizers (PCFs). Source: adapted from Kassem et al. 2024.*

Polymer coatings have also been developed which claim to increase NuUE through chemical interaction with soil constituents that reduce P availability (Al, Fe or Ca), but there is considerable scientific debate regarding the agronomic efficacy of these coatings and the claimed mode of action has not been clearly demonstrated at commercial application rates.

A more recent advance is the commercial development of biological coatings formulated for application to traditional granular (e.g., urea, monomammonium phosphate (MAP), diammonium phosphate (DAP), triple superphosphate (TSP) or fluid fertilizers (e.g., urea ammonium nitrate (UAN), ammonium polyphosphate (APP), liquid trace elements). Some of these even claim to increase NuUE of the base product. These can be comprised of either living bacteria or fungi or their spores, or enzymes. Only little published information is available on whether these microorganisms survive or the enzymes remain active after having been applied to soil, their mode of action, or effects on crop yield. The chemical environment of soil pore water surrounding a soluble fertilizer granule or fertilizer liquid (e.g., urea ammonium nitrate, ammonium polyphosphate, liquid trace elements) after addition to soil is not conducive to survival of microorganisms due to high solution ionic strength, often adverse solution pH and in some cases high concentrations of potentially toxic elements such as Zn. Innovation in microbial coatings for commonly used water-soluble fertilizers will need to develop formulations that maximize microbial survival and growth. Burke et al., for example, showed that self-assembled nanocoatings can protect microbial fertilizers.

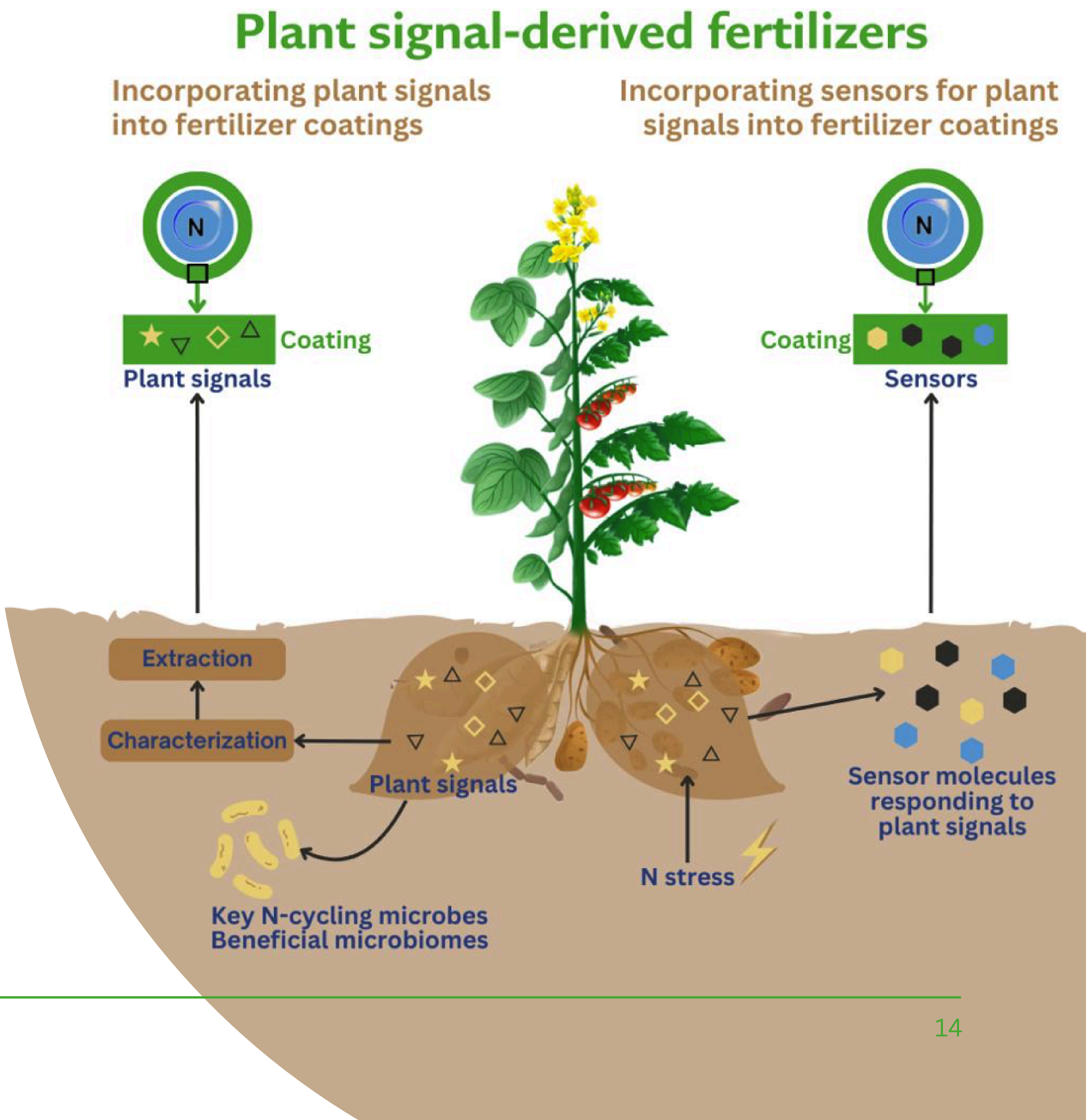
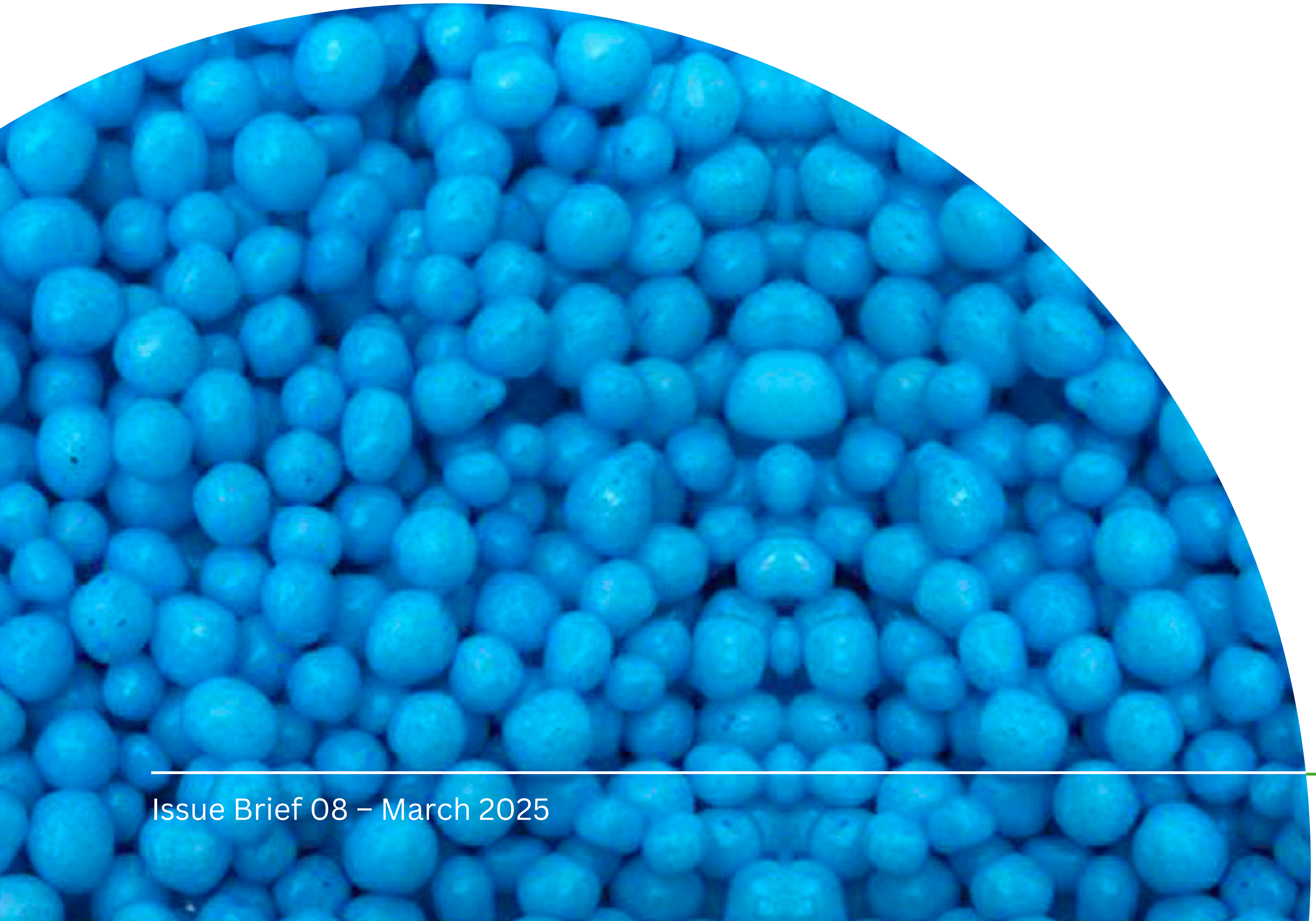


Figure 6. *Future 'smart' fertilizers may contain coatings that enable nutrient release in response to plant signals. Source: adapted from Lam et al. 2022.*

Carrier technologies

This group of technologies is based on the principle that nutrients can be loaded onto a “carrier” structure that may be comprised of nutrients or non-nutritional elements. Usually, the carrier matrix in some way modifies the release of nutrients so that the resulting fertilizer has different release characteristics than highly soluble fertilizers. Below we describe three categories of carrier materials.



Layered double hydroxides

Layered double hydroxides (LDH) comprise a class of materials consisting of positively charged layers of metal hydroxides. Between the layers, negatively charged ions and water molecules balance the charge. This class of material is often described as "anionic clays" because they can exchange the interlayer anions, making them useful for use as fertilizers. Layered double hydroxides have the general formula

$$\mathrm{LDH{-}M_2{+}1{-}xM_3{+}x(OH)_2(Am{-})x/m{\cdot}nH_2O}$$

where M is a metal and A is an anion. Originally, these natural or synthetic minerals were applied to remove anionic pollutants from water supplies, including phosphate. Quickly interest arose to use the P-loaded materials as fertilizers and more recently for development of new slow-release molybdenum fertilizers. The release of P from P-loaded-LDH fertilizers was found to be slow but the agronomic efficiency exceeded that of soluble P fertilizers in acidic soils by up to 4.5 fold, but RE values were still extremely low (<3%). Subsequently the better agronomic performance of the LDH was found to be due to the dissolution of the LDH acting as a liming agent in the soil rather than due to the P release characteristics of the fertilizer.

As for many slow-release P sources, fertilizer form and placement are critical for the dissolution and effectiveness for crop uptake. Granulation of the powdered materials dramatically reduces dissolution and crop acquisition of nutrients. Hence, agronomic evaluations need to be performed with the product form most likely to be used by farmers. A further limitation of LDHs is the nutrient content of the final products when the carrier backbone often comprises non-nutritive elements not normally added to soil (e.g. Al, Fe), resulting in low fertilizer nutrient contents e.g. <10% P.

Metal organic frameworks

Metal-organic frameworks (MOFs, Fig. 7) are porous molecular structures comprised of metal ions (e.g. Cu, Fe-, Zn, etc.) linked by organic molecules. The pores in the structure can be designed to retain gases or ions making MOFs suitable for applications in many industries. The potential application of MOFs for fertilizer formulation has been reported relatively recently. The mode of action of these materials is to trap or hold nutrients within the pore structure and release them slowly as the organic linkers slowly degrade in soil.

Similar to LDH materials, there are benefits if the metals in the structure are plant nutrients (normally required to be soil-applied), rendering the nutrient content of the formulation high. The feasibility of scale-up of MOF fertilizer production has recently been demonstrated. However, significant yield advantages or cost savings from using these materials as fertilizers over conventional products have yet to be widely demonstrated.

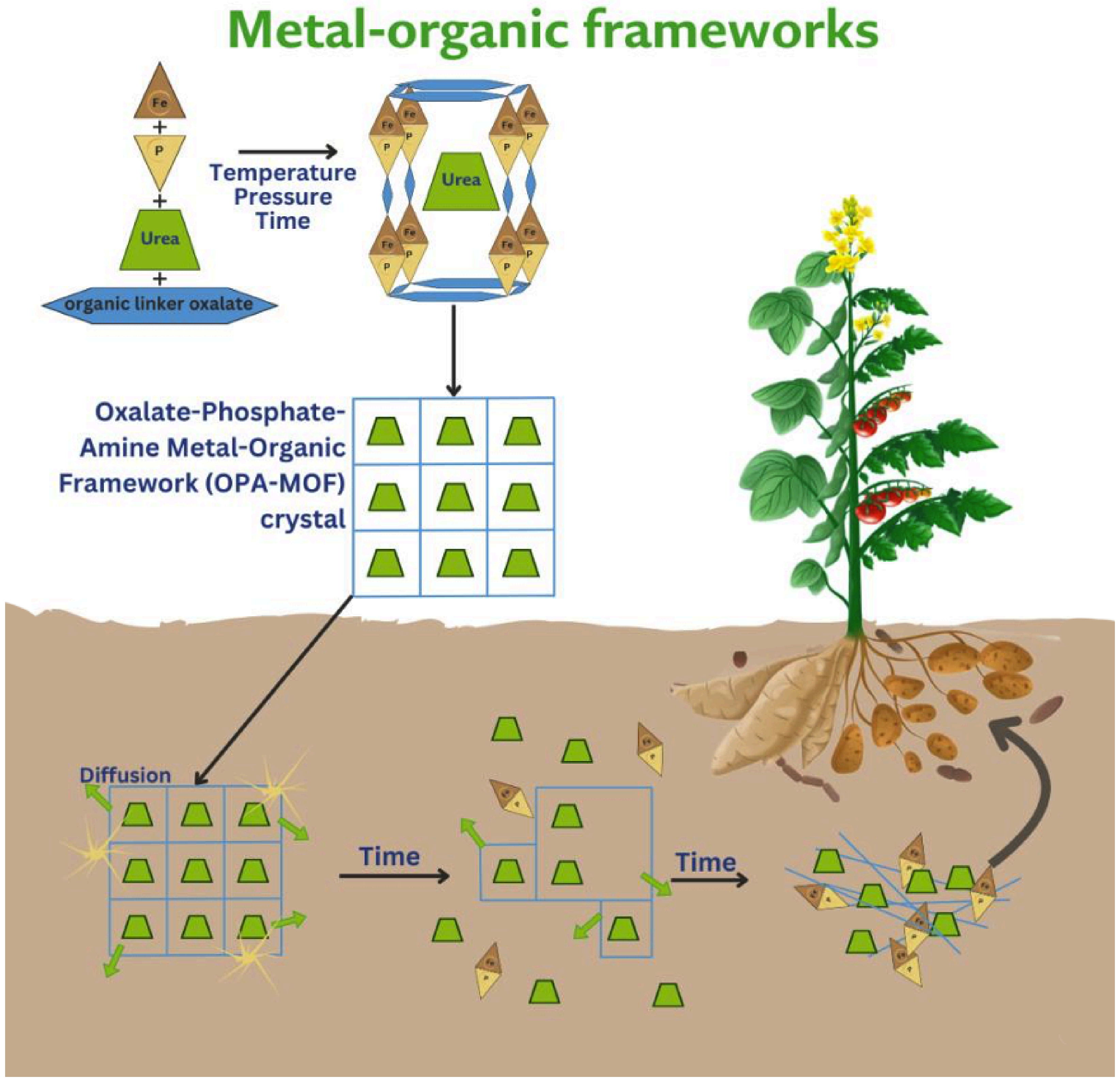
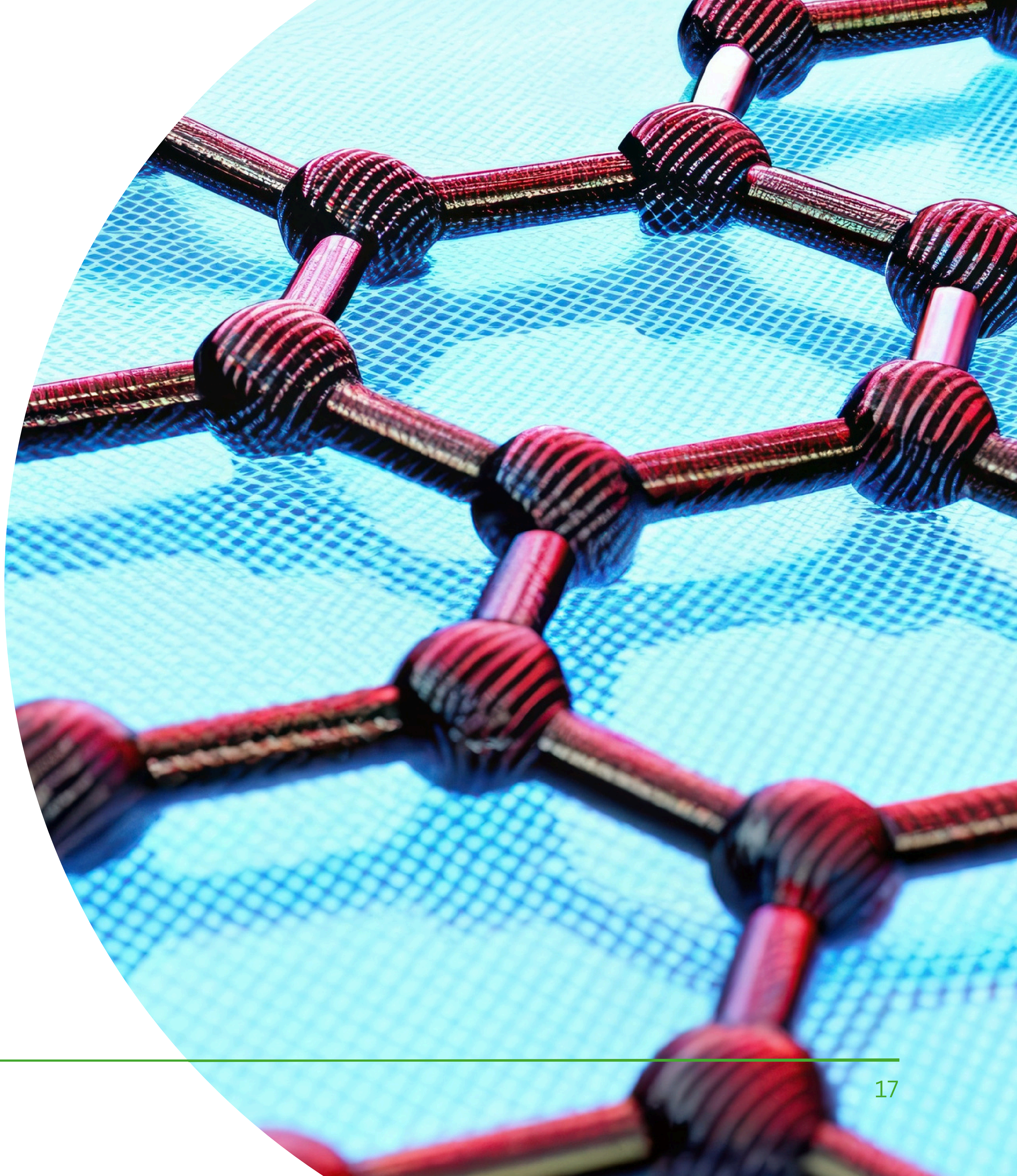


Figure 7. *Basic design of a N, P, and Fe- based metal-organic frameworks and their modes of action after addition to soil. Source: adapted from Anstoetz et al. 2015.*



Graphene-based materials

Graphene, a material discovered in 2004, comprises ultrathin 2-dimensional sheets of carbon atoms with unique chemical and physical properties that have resulted in broad applications of this material in industry. Graphene can be oxidized to graphene oxide to impart a strong negative charge to the material surface, allowing cationic nutrient retention or anionic nutrient attachment through cation bridges. Zhang et al. were the first using graphene oxide as a coating material on potassium nitrate (KNO_3) granules to impart slow-release characteristics to the fertilizer. Since then, several studies have examined the ability of graphene-based materials to either act as carriers for nutrients, as coatings to slow nutrient release, or to improve fertilizer physical quality.

As with other carrier technologies, one of the issues with the use of graphene-based materials as fertilizers is the dilution of nutrient contents in the final formulation due to the C in the carrier material. Graphene-based C from fertilizers is unlikely to benefit soil health as it is not a C source for microorganisms and could raise concerns due to persistence in soil. Furthermore, the costs of raw materials and production scale-up could impede the commercial adoption of this fertilizer technology. Finally, the efficacy testing of any new formulations needs to move from the laboratory/glasshouse to the manufacturing plant and the field for commercial acceptance and implementation.

Nanomaterials

Nanomaterials are materials containing 50% or more particulates or constituents of at least one dimension in the range of 1-100 nm. Nanomaterials are interesting because the behavior of material at nanoscale is dramatically different from that of the same bulk-sized material, as the surface area-to-volume ratio is so large. Furthermore, due to their small size and depending on the surface charge, nanomaterials may be more mobile in soils than the equivalent nutrient in ionic form. Hence, they may enter plants through different routes than nutrients in ionic form. Over the last 15 years, several reviews have examined the potential application of nanomaterials for fertilizer design, either as nanomaterials or as nanocarriers for nutrients. These are all effectively novel suspension fertilizers with the suspended solids nanosized. Some nanofertilizers could offer non-nutritional benefits to plant growth by acting as biostimulants. For example, they could increase the efficiency of photosynthesis by extending the light response range of chloroplasts and enhancing electron shuttling. As only small amounts of nutrients can be applied to plant leaves via the foliar route, nanosized micronutrient fertilizers are likely to be more agronomically successful than nanosized macronutrient foliar fertilizers.

Nano-enabled precision delivery of nutrients or other molecules to plants is still developing, with significant scientific and societal barriers to overcome. There are currently more than 600 journal publications with nanofertilizer in their titles (ISI Web of Science, accessed February 2025), but with the notable exception of products such as Nano-Urea or Nano-DAP in India their commercial applications have remained very limited. In many cases, rigorous agronomic evaluation of soil-applied nanofertilizers under field conditions is lacking, while occupational health concerns criticize the logistics of applying nanofertilizers, except as liquid suspensions. Long-term environmental or health risks from introducing nanoparticles regularly into managed and natural ecosystems and their food chains are still to be fully evaluated.

Nanofertilizers have also been evaluated under glasshouse conditions, but these studies often lack rigor too. Even though the fate of nanoparticles in soil is poorly studied, soil nanotoxicology studies have shown that nanomaterials aggregate with soil colloids (heteroaggregation) quickly losing their “nano” form. Foliar nanofertilizers have been suggested to be more effective than conventional foliar fertilizers. While results from fundamental mechanistic studies indicate novel modes of entry into plants and translocation, the efficacy claims in relation to conventional products are not robustly supported yet and large gaps in rigorous field evaluation remain. As noted above, nanomaterials have been proposed as coatings for fertilizers containing beneficial microorganisms to improve microbial survival, but again commercial implementation has yet to occur.

In this rapidly changing field, an early meta-analysis of the efficacy of nanofertilizers compared to conventional products suggested that NuUE could be increased up to 29%. However, the cost of manufacturing nanofertilizers has been raised as an impediment to widespread adoption, even when assuming much higher NuUE than for conventional products (7 to 27-fold higher NuUE). Clearly, as the efficiency of conventional nutrient use currently lies between 10 and 80%, the scope to raise NuUE by more than 10-fold is limited.

The first nanofertilizers, nano-Urea and nano-DAP in particular, have recently been commercialized in India (*see references at the end*), providing a case study from which much can be learned. Scientists have raised concerns that should be addressed, particularly in terms of underlying scientific understanding of the mode of action as well as in terms of rigorous field evaluation. Although hydroponic studies have provided first indications for biostimulatory effects of nano urea on N assimilation and chlorophyll biosynthesis, research so far has not yet elucidated a clear (plausible) mode of action. Besides that, many of the field trials that have been conducted so far have methodological gaps in terms of treatment design (e.g. lack of proper controls, lack of full N response curves, N rates used), measurements, or data analysis and interpretation. In the end, independent agronomic and economic evaluation of new nanoproducts will determine which nanofertilizers are effective and economic for farmers to use (see below).

Barriers to wider commercial use of novel fertilizer technologies

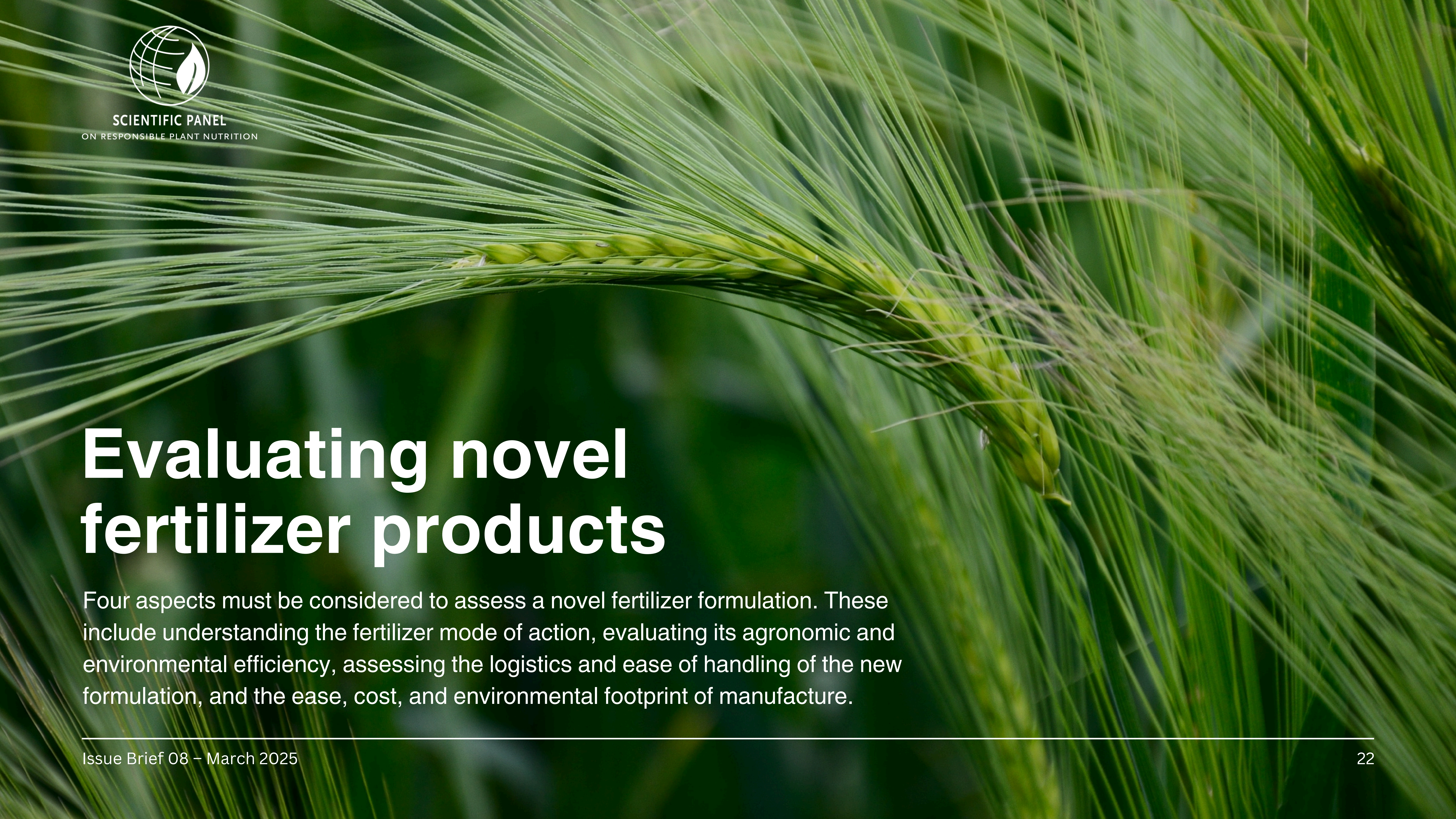
The commercial use of fertilizers globally is still dominated by “commodity products” such as urea, MAP, DAP, muriate of potash (MOP) etc., based on technology that was developed in the middle of the last century. Besides an increasing diversity of formulations and nutrient combinations in fertilizer products, probably the most widely used innovations in fertilizer technology since then have been the inhibitors used to “stabilize” N products and fertilizer coatings to slow or control nutrient (principally N) release. Yet, these still only constitute a small percentage of the global fertilizer market today. Why is this?

Current EEFs tend to be more expensive than conventional products and the agronomic or NuUE benefits are often not large compared to the additional cost. Most farmers require a clear economic benefit to be demonstrated before adopting a new technology unless other broader incentives are offered. For example, in the United States, initiatives like the Environmental Quality Incentives Program and the Conservation Stewardship Program offer financial and technical assistance to farmers adopting EEFs, including stabilized N products. These programs aim to reduce N losses while supporting crop productivity and environmental sustainability. In Canada, initiatives such as the Canola 4R Advantage Program, supported by the On-Farm Climate Action Fund, provide incentives for implementing 4R Nutrient Stewardship practices, which include the use of EEFs like stabilized N fertilizers.

Numerous scientific publications explore the development of novel fertilizer formulations. Yet, few of the suggested technologies are available as commercial products for farmers. Why is this? First, we need to consider and close the “recovery efficiency gap” – on average plants recover 40%-60% of the N and K applied in fertilizers. In comparison, fertilizer P RE varies from <10% in P-deficient soils to >80% in soils with a long history of fertilizer use. Many efficiency gains are limited when tested under realistic field conditions; hence, exaggerated claims for efficiency improvements should be viewed cautiously.

Many emerging technologies described in the scientific literature will fail to be commercially developed because the benefits of the innovation in terms of yield, NuUE, or environmental protection are not significant enough to warrant the increased costs of production or application. Furthermore, many issues unrelated to agronomy, NuUE, or environmental benefits need to be satisfied for effective commercialization of any new technology – costs of energy and raw materials, security of supply of raw materials, new capital requirements for manufacture, scalability of manufacturing, logistics and costs of transport, handling and applying new products, and occupational health and safety considerations. These issues are rarely considered in research publications.

Finally, there may be policy or regulatory barriers to the adoption of new technologies, e.g. environmental and human health concerns regarding microplastics (from polymer coatings), nanomaterials, possible food chain transfer of new chemicals, etc. These require consideration at an early stage of new product development and appropriate information and data gathered to provide confidence in product safety.



Evaluating novel fertilizer products

Four aspects must be considered to assess a novel fertilizer formulation. These include understanding the fertilizer mode of action, evaluating its agronomic and environmental efficiency, assessing the logistics and ease of handling of the new formulation, and the ease, cost, and environmental footprint of manufacture.

Mode of action

The claimed mode of action should be tested, disclosed (published), and verified. Experimentation to verify the mode of action will depend mainly on the fertilizer type and the nature of the invention. For example, a new N product that claims to delay the release of plant-available N forms needs to be assessed for the kinetics of N release, preferably in soil, and compared to N release from a reference fertilizer commonly used by farmers. A new product that claims to release P from unavailable forms in soil needs to be tested for dissolution/release of P to soil solution from the solid phase in soil, preferably using isotopic dilution principles, which can measure both P in solution and P adsorbed to the solid phase that is in equilibrium with the soil solution. A nanofertilizer claiming to increase crop yield or nutrient use efficiency needs to be tested for any direct nutrient delivery effects involved, as well as any biostimulatory responses that may affect growth. Understanding modes of action requires detailed research using advanced scientific techniques. For example, studying the movement of nanoparticles in soils or plants requires great care and several different techniques, including different labeling techniques. Likewise, analysis of detailed gene expression as well as physiological measurements are required to unravel specific (hormonal) responses to the application of a product that may, in addition to carrying nutrients, act as a biostimulant.

Agronomic and environmental performance

Agronomic as well as environmental efficiency gains claimed need to be verified. Early indications of RE of a new product can be gained under controlled environment or glasshouse conditions given appropriate experimental methods, i.e. similar product amount, form and placement as intended for field use. To assess new products, too often glasshouse experimentation uses inappropriate growth media e.g. vermiculite, perlite, potting mixes, pure sand and unrepresentative product amounts, form, and placement (e.g., fine powders uniformly mixed through soil when the intended product will be banded in granular form under field conditions).

Ultimately, and as early as possible, performance of new products must be evaluated under field conditions. General guidelines for evaluating novel plant nutrition solutions have recently been proposed.

Guidelines for Assessing Enhanced Efficiency Fertilizer Products:

- A scientific committee created protocols focusing on experimental design, crop, and soil measurements, environmental loss assessments, and data stewardship.
- Guidelines were developed with input from international researchers, industry stakeholders, and agricultural organizations to standardize EEF research, foster data sharing, and enhance the scientific understanding of EEFs.

Core Experimental Design Components and Minimum Data Sets:

- Trials must include control treatments, standard fertilizer comparisons, and varying rates of EEFs.
- Proper replication, blocking, and inclusion of key metadata (e.g., field history, soil properties) are required for robust results.
- Consistent collection of essential data ensures comparability and integration across trials.
- Metadata includes soil and crop history, environmental conditions, and trial methodologies.

Three-Tier Framework:

- Tier 1: Experimental design and metadata
- Tier 2: Agronomic and soil performance metrics
- Tier 3: Measurements of environmental losses (e.g., nutrient runoff and gaseous emissions)

Environmental Impact Measurements:

- Methods for assessing nutrient loss via water (e.g., nitrate leaching) and gaseous emissions (e.g., nitrous oxide and ammonia)

Field evaluation should occur over multiple sites/years and with the appropriate crop type (for that product), placement, and management. Naturally, the site/soil/crop combination needs to be deficient in the nutrient(s) being evaluated. Experimental designs require appropriate control plots (no nutrient added). For example, a field experiment in which a foliar-applied product is evaluated requires a control which receives only water while all other nutrient inputs are the same. Likewise, to evaluate whether a foliar-applied nanofertilizer may also have a biostimulant effect requires an additional control to which only the dissolved nutrient is foliar applied, without nano-particles.

Another issue frequently found is comparing products at inappropriate rates of addition. For example, in many field trials, applying novel fertilizer products in combination with a reduced or full 'recommended N rate' is compared to N application at the recommended N rate. However, if the recommended N rate was too high to begin with (not agronomically or economically optimal), a reduced N rate is likely to result in the same (or even slightly higher yield), irrespective of whether a novel product was applied or not. This phenomenon has been particularly common in recent studies on nanofertilizers and microbial products . To properly assess the efficacy of such product requires conducting field trials that include at least 4-5 different N levels, each with and without the new product to be evaluated. This will allow estimating performance of the new product at the optimal N rate derived from the N response curve.

Several other design requirements are also recommended for appropriate statistical analysis of the data – randomization, replication, and robust statistical analysis of data. The combinations of crop responses to the new product over multiple sites/soils/years into a cumulative probability distribution is a compelling way to evaluate new product efficacy. As elegantly demonstrated by Karamanos et al., incorrectly parameterized statistical analysis can easily lead to false positives (Type 1 errors).

Physical quality, handling, and safety

Along with the agronomic efficiency of the product, the logistics and ease of handling of the new formulation is equally important. The product should be physically robust – for granular products this means good granule hardness, low hygroscopicity, good abrasion resistance, low dust generation, low caking tendency, and good flowability. Compatibility for blending with other fertilizers should also be evaluated. For new liquids/suspension products, these should also be physically stable and not prone to precipitation or settling. Development of new products also needs to ensure that new formulations do not pose occupational health or safety concerns in manufacturing or handling by farmers due to their physical characteristics, e.g. nanodusts or other hazardous respirable ingredients.

Manufacture

Developing new formulations needs to consider manufacturing issues, such as raw material costs, availability and security of supply, capital costs of installing new equipment for manufacturing, manufacturing complexity and scalability, energy inputs, as well as waste stream production and treatment.

The reason many new fertilizer formulations identified in the scientific literature fail to gain commercial success is that they do not adequately consider all the above factors and perhaps focus too heavily on only one or two of the key requirements. Exploring different product designs and scalability in terms of manufacturing and cost should become an integral part of the innovation process, at an earlier stage than often done.

Who needs to do what?

Governments:

Adopt policies and establish programs that work across the multiple sectors of government, industry, and academia to incentivize and reward innovation in fertilizer technologies. Improve and streamline regulatory frameworks where efficacy is demonstrated independently and with scientifically rigorous protocols agreed internationally. Promote knowledge sharing, education, and collaboration across sectors and incentivize circular economy approaches. If appropriate, provide financial incentives for technology adoption.

Industry:

Provide resources and drive innovation both internally and externally to develop new fertilizer technologies. Collaborate with government and academic scientists to develop EEFs that minimize adverse impacts on the environment including stabilized N fertilizers, smart/controlled release fertilizers, and disruptive technologies. Evaluate new products using agreed protocols which are more robust and transparent (83). Set carbon reduction targets and commit to sustainability goals. Transparently communicate product characteristics and benefits.

Researchers:

Innovate technologies that enhance NuUE and minimize environmental harm. Work more closely with industry scientists and engineers at early stages to develop products that can be formulated and manufactured at low cost and with low energy requirements. Work across disciplines to bring new thinking and innovations into fertilizer design. Evaluate cost/benefits of new products at an early stage in research programs and work with farmers/practitioners to identify formulations that are most feasible, practical, and safe at the farm level. Be critical of your own innovations, move quickly to rigorous field evaluation and rely on robust, standardized evaluation guidelines (83). Publish research in open-access journals (if possible) and communicate both negative and positive agronomic and NuUE results.

Farmers and other practitioners:

Engage with field evaluation programs for new fertilizer products, provide robust feedback on ease of handling and on-farm performance. Advocate for more sustainable products, demand transparency in performance, and support local innovators.

What would success look like?

1

Many novel fertilizers become available that increase crop yields and nutrient use efficiency, further reduce GHG emissions and other nutrient losses to the environment, improve food quality, have better-handling characteristics, have a lower energy footprint for manufacture and minimize the production of waste streams.

2

Governments adopt evidence-based criteria for registering and labeling new fertilizer products that include independent assessment of agronomic and environmental performance.

3

Industry increases resources directed towards new fertilizer technologies and develops partnerships with government/academia to drive innovation, and more widely uses standardized experimental protocols to evaluate the agronomic and environmental performance of new fertilizer products. Governments and other investors provide incentives for multi-sector research projects to develop new fertilizer products encouraging public-private partnerships as well as more open, pre-competitive research on novel modes of action, materials, formulations etc.

4

Farmers have access to a wider range of fertilizer products with proven performance benefits, and participate in fertilizer evaluation programs using harmonized protocols. Product performance information becomes more transparent and available to farmers to make informed choices.

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