



Innovative Crop Nutrition Technologies: From Fertilizer Development to Field Validation

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ABSTRACT :

Sustainable intensification requires fertilizer products that deliver nutrients at biologically appropriate rates while minimizing loss pathways and protecting soil function. This review integrates mineral nutrition, soil–root processes, formulation chemistry, enhanced-efficiency fertilizers (EEFs), biological nutrient sources, laboratory quality control, crop-specific agronomy and multi-environment field validation into a single product-development perspective. It compares conventional granular NPK, water-soluble, suspension, stabilized, micronutrient, coated and nano-enabled fertilizers, together with microbial inoculants and biostimulants; explains how pH, moisture, temperature and microbial processes shape performance; and proposes a stage-gated research-to-commercialization framework with prespecified go/no-go criteria. The distinction between laboratory nutrient-release behavior and field agronomic superiority is emphasized: reliable claims require nutrient-equivalent controls, randomized and replicated multi-location trials, mixed-model analysis, economic assessment and evaluation of environmental trade-offs. Emerging biodegradable coatings, sensor-guided nutrient management and data-driven formulation optimization are promising but must be tested for field reliability, regulatory acceptability and life-cycle impacts. A claim–evidence matrix is provided to help developers, regulators and researchers match product claims to the evidence needed to support them.

Keywords: crop nutrition; nutrient use efficiency; enhanced-efficiency fertilizers; controlled-release fertilizers; rhizosphere; biostimulants; integrated nutrient management; field validation

1. Introduction

Mineral fertilizers are one of the main technological foundations of modern food production. Synthetic nitrogen alone is estimated to sustain a large share of the world's population (Erisman et al., 2008; Smil, 2001), and balanced nutrient management remains central to closing yield gaps (Mueller et al., 2012; Tilman et al., 2002).

The same inputs are, however, used inefficiently in many systems. The fraction of applied nutrient recovered by the crop is frequently low: nitrogen is lost through nitrate leaching, ammonia volatilization and denitrification, whereas phosphorus is rapidly sorbed or precipitated in soil, so that only a modest fraction is usually taken up in the season of application (Cassman et al., 2002; Ladha et al., 2005; Syers et al., 2008; Lassaletta et al., 2014). These losses carry both an economic cost to farmers and an environmental burden through nitrate contamination of water, nitrous oxide emissions and eutrophication (Vitousek et al., 2009; Sutton et al., 2013; Zhang et al., 2015; Bijay-Singh & Craswell, 2021). Integrated soil–crop management studies in China indicate that higher yields and lower environmental costs can be achieved together when nutrient supply is matched more closely to crop demand (Ju et al., 2009; Chen et al., 2014).

The central challenge is therefore not simply supplying more nutrients, but synchronizing nutrient supply with the temporal and spatial demands of roots and shoots. Fertilizer effectiveness varies with soil buffering, crop genetics, irrigation and weather (Marschner, 2012; Zhang et al., 2010; Bindraban et al., 2015). A growing set of technologies—enhanced-efficiency fertilizers, micronutrient chelates, biological inoculants and biostimulants, nano-enabled carriers and sensor-guided decision tools—aims to improve this synchronization. Claims for these technologies are, however, often supported by laboratory release curves or single-site pot studies rather than by field evidence at nutrient-equivalent rates.

Existing reviews tend to address formulation chemistry (Shaviv, 2001; Trenkel, 2010; Timilsena et al., 2015; Lawencia et al., 2021), rhizosphere biology (Zhang et al., 2010) or biological inputs (Bashan et al., 2014; Calvo et al., 2014) in isolation. This review integrates these perspectives into a product-development viewpoint with three aims: (i) to summarize the physiological and soil-chemical basis of nutrient-supply strategies; (ii) to compare formulation platforms and biological inputs, highlighting the evidence needed to support performance claims; and (iii) to propose a stage-gated framework that links formulation, analytical quality control, field validation, economics and regulation. The review is narrative rather than systematic: sources were

selected for relevance and quality, giving priority to peer-reviewed reviews, multi-site field evidence, standard textbooks and regulatory documents, and quantitative conclusions are therefore stated cautiously.

2. Scientific Foundations of Crop Nutrition

2.1. Essential nutrients and diagnostic limitations

Nitrogen is a constituent of amino acids, proteins, nucleic acids and chlorophyll; phosphorus is integral to phosphorylated metabolites, nucleic acids and membranes; and potassium regulates osmotic functions and activates numerous enzymes. Calcium, magnesium, sulfur and the micronutrients underpin membrane and cell-wall stability, photosynthesis, amino acid formation and enzyme function (Fageria, 2009; Marschner, 2012). The phloem mobility of an element determines whether deficiency appears first on older or younger tissue (Table 1). Because visual symptoms overlap with those of drought, salinity, disease and herbicide injury, deficiency diagnoses should be confirmed by soil and plant-tissue analysis (Fageria, 2009; Havlin et al., 2014; Marschner, 2012).

Table 1. Selected nutrient functions, phloem mobility and diagnostic limitations.

Nutrient	Principal physiological role	Phloem mobility	Diagnostic caution
N	Amino acids, proteins, chlorophyll	High	Chlorosis is not uniquely N deficiency
P	Energy metabolism, nucleic acids, membranes	High	Purple coloration is not universal
K	Osmoregulation; enzyme activation	High	Symptoms resemble drought or salinity stress
Mg	Chlorophyll constituent; enzyme cofactor	High	Interveinal chlorosis can mimic other disorders
Ca	Cell-wall and membrane stability	Low	Disorders often reflect transport, not soil supply
S	Cysteine, methionine; coenzymes	Intermediate	Early symptoms resemble N deficiency
Zn	Enzyme function; protein synthesis	Intermediate	Soil pH and high P supply alter availability
Fe	Electron transport; chlorophyll synthesis	Low	Chlorosis has multiple causes (e.g., calcareous soil, waterlogging)

Referred from Marschner (2012) and Fageria (2009).

2.2. Nutrient acquisition by roots

Roots acquire ions through mass flow, diffusion and root interception. Nitrate moves readily with the soil solution, whereas phosphate is strongly sorbed, present at very low solution concentrations and transported mainly by diffusion over distances of only a few millimetres; uptake therefore depends on root surface area, root hairs, exudation and mycorrhizal association (Hinsinger, 2001; Shen et al., 2011). Root architecture is plastic and responds to local nutrient patches, which has implications for placement (Lynch, 1995). Transporter regulation, exudation and microbial symbioses further modulate uptake and should inform nutrient placement and formulation design (Zhang et al., 2010).

2.3. Nutrient interactions and efficiency concepts

Nutrients interact. Balanced N–P–K supply often produces synergistic responses, whereas antagonisms arise when, for example, high phosphorus supply aggravates zinc deficiency or when excess K^+ or NH_4^+ restricts Mg^{2+} and Ca^{2+} uptake (Fageria, 2009; Marschner, 2012). A single-nutrient response curve therefore cannot be extrapolated to mixed grades without testing. Micronutrient deficiencies, especially of zinc and iron, can limit yield and grain nutritional quality even where macronutrient supply is adequate, which has motivated agronomic biofortification strategies (Alloway, 2008; Cakmak, 2008).

Nutrient use efficiency (NUE) is not a single metric but a family of indices—agronomic efficiency, apparent recovery efficiency, partial factor productivity and internal efficiency—that answer different questions and must be interpreted together with their control treatments (Baligar et al., 2001; Cassman et al., 2002). These indices are defined in Section 8.

3. Soil–Plant–Water–Nutrient Interactions

3.1. Soil chemical and physical properties

Soil pH alters phosphate reactions and micronutrient solubility. Phosphate availability is generally greatest in slightly acidic to neutral soils because phosphate is fixed by iron and aluminum compounds at low pH and by calcium at high pH (Hinsinger, 2001; Havlin et al., 2014). In acidic soils, aluminum toxicity can restrict rooting, whereas in alkaline or calcareous soils zinc, iron and manganese become poorly available (Alloway, 2008; Marschner, 2012). Cation exchange capacity and clay mineralogy control potassium buffering, and organic matter affects nutrient cycling, aggregate stability and water retention (Havlin et al., 2014). These properties explain why the same product can perform differently on a light-textured Alfisol and a heavy-textured Vertisol, and why site characterization is a mandatory component of trial design (Section 8).

3.2. Moisture, temperature and redox status

Moisture regulates fertilizer dissolution, solute diffusion and nutrient transport. Temperature governs urea hydrolysis, nitrification and the diffusion-controlled release of polymer-coated products (Shaviv, 2001; Trenkel, 2010). Saturation favors denitrification in susceptible soils, whereas drying limits diffusion and biological activity. In flooded rice, N is lost through coupled nitrification–denitrification and through ammonia volatilization from floodwater, so that fertilizer N recovery in cereal systems is often low (Ladha et al., 2005). Release rates measured at a single laboratory temperature therefore cannot by themselves predict field nutrient supply.

3.3. Rhizosphere processes

Rhizosphere processes—root-induced pH change, release of organic acids and phosphatases, and microbial transformations—can mobilize sparingly soluble phosphorus and micronutrients and influence nitrogen turnover (Jones, 1998; Zhang et al., 2010; Richardson & Simpson, 2011). Rhizosphere management is thus a lever for improving nutrient efficiency, but responses to microbial inoculants are strongly context dependent and are influenced by competition with native populations (Bashan et al., 2014).

4. Innovative Fertilizer Formulation Technologies

4.1. Conventional platforms

Granular NPK formulations are robust, familiar and compatible with existing handling infrastructure, but they may deliver nutrients faster than crop demand (Figure 1). Water-soluble fertilizers support fertigation and targeted delivery, yet concentrated tank mixtures can precipitate when calcium is combined with incompatible phosphate or sulfate sources, and salt index, chloride content and water quality must be considered. Suspension fertilizers allow high nutrient loading but require careful control of particle size, dispersants and rheology to avoid settling and nozzle blockage. For every platform, formulation is an engineering problem constrained by nutrient grade, physical properties, cost and manufacturability, rather than purely a chemistry problem (see also Singh & Pandey, 2026b).

4.2. Enhanced-efficiency fertilizers

The literature distinguishes three groups of EEFs (Trenkel, 2010; Timilsena et al., 2015). Slow-release fertilizers contain low-solubility compounds, such as urea–aldehyde condensates, whose release depends on chemical or microbial decomposition and is difficult to predict. Controlled-release fertilizers (CRFs) enclose soluble nutrients in a coating or matrix whose permeability, and hence release rate, is governed by identifiable factors, chiefly temperature and moisture. Stabilized fertilizers carry urease or nitrification inhibitors that delay selected N transformations rather than physically enclosing the nutrient (Table 2).

Comparative interpretation is essential: a formulation with slower nutrient release is not necessarily agronomically superior. The relevant benchmark is a nutrient-equivalent, well-managed conventional treatment, including split applications where appropriate. Performance should be assessed by crop uptake, yield, loss pathways and economic return, not by a laboratory release curve alone (Shaviv, 2001; Trenkel, 2010; Timilsena et al., 2015).

Table 2. Categories of enhanced-efficiency fertilizers (EEFs): mechanisms and principal sensitivities.

Category	Mechanism	Principal sensitivities	Key references
Sulfur-coated urea	Physical barrier; release through coating defects and degradation	Coating integrity, abrasion during handling, microbial degradation of S	Trenkel (2010)
Polymer-coated (CRF)	Diffusion through a semi-permeable membrane	Temperature, moisture, coating composition and thickness	Shaviv (2001); Azeem et al. (2014)
Slow-release (low-solubility) compounds	Chemical or microbial decomposition of condensates (e.g., urea-aldehyde)	Soil temperature, pH, microbial activity	Trenkel (2010)
Urease inhibitors	Delay urea hydrolysis (e.g., NBPT)	Temperature, moisture, stability on the granule	Trenkel (2010); Timilsena et al. (2015)
Nitrification inhibitors	Suppress ammonia oxidation (e.g., DCD, DMPP, nitrapyrin)	Temperature, soil texture and organic matter, degradation rate	Subbarao et al. (2006)
Bio-based coatings	Diffusion through biodegradable polymer films	Realism of biodegradation, mechanical strength, cost	Chen et al. (2018); Lawrence et al. (2021)

NBPT, N-(n-butyl) thiophosphoric triamide; DCD, dicyandiamide; DMPP, 3,4-dimethylpyrazole phosphate; CRF, controlled-release fertilizer.

In polymer-coated products, water vapor penetrates the coating and dissolves the nutrient, and the resulting solution diffuses out through the coating; coating composition and thickness, temperature and coating integrity therefore control release (Shaviv, 2001; Azeem et al., 2014; Lawrence et al., 2021). Accelerated laboratory tests performed at constant temperature in water may not predict behavior in soil with fluctuating temperature and moisture and with mechanical damage during handling (Shaviv, 2001; Lawrence et al., 2021). Inhibitor efficacy is likewise environment dependent: nitrification inhibitors vary with temperature, soil texture and organic matter, and may shift N loss between pathways—for example from nitrate leaching toward ammonia volatilization—unless the whole system is evaluated (Subbarao et al., 2006; Trenkel, 2010).

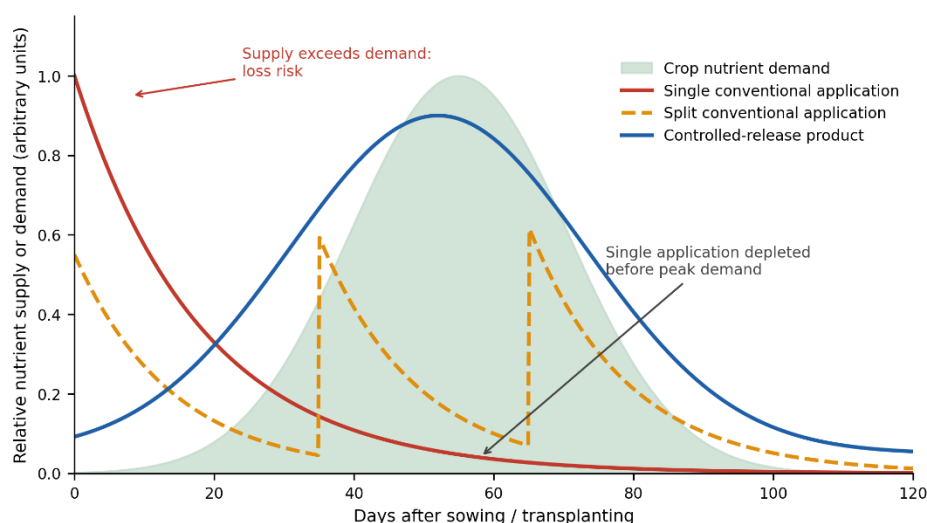


Figure 1. Conceptual comparison of nutrient supply patterns and crop nutrient demand. A single conventional application supplies nutrient before demand peaks, whereas split application and controlled-release products shift supply toward the period of highest demand. The curves are illustrative and are not experimental data.

4.3. Micronutrient fertilizers

Micronutrient fertilizers are formulated as inorganic salts, oxides or chelates. Chelated forms, such as Fe-EDDHA in calcareous soils, can maintain solubility where inorganic sources are rapidly immobilized, but cost and ligand stability under soil conditions constrain their use (Marschner, 2012; Dimkpa & Bindraban, 2016). Granulating or coating micronutrients with macronutrient carriers improves distribution and allows controlled-release designs for precision agriculture (Mikula et al., 2020). Foliar application offers a rapid corrective route but requires evaluation of concentration, crop safety and timing (Section 10).

4.4. Bio-based and biodegradable coatings

Bio-based polymers (for example starch-, cellulose-, lignin- or chitosan-derived materials) and mineral–polymer composites may reduce reliance on persistent synthetic polymers. Claims of biodegradability, however, require testing under realistic soil conditions with defined endpoints, and release behavior, mechanical strength and cost must be compared with established coatings (Chen et al., 2018; Lawrencina et al., 2021).

Coating selection requires an explicit trade-off among barrier properties, abrasion resistance, process temperature, feedstock variability and environmental fate. Sulfur coatings can be sensitive to defects; synthetic polymer membranes offer tunable diffusion but require residue assessment; and starch-, cellulose-, lignin- and chitosan-based films may face moisture sensitivity or scale-up constraints. These are technology-dependent considerations rather than evidence of universal superiority (Azeem et al., 2014; Chen et al., 2018; Lawrencina et al., 2021).

4.5. Nano-enabled carriers

Nano-enabled carriers and nanostructured nutrient sources may improve targeting and reduce application rates, but independent field-scale evidence is still limited. Particle fate, ecotoxicity, human safety, cost and regulatory classification warrant separate assessment (Kah et al., 2019; Lowry et al., 2019; Lawrencina et al., 2021). Table 3 summarizes the main platforms discussed in this section.

Table 3. Comparison of fertilizer technology platforms.

Platform	Potential value	Primary limitation	Maturity ^a
Granular NPK	Simple broad-acre delivery	Limited release synchronization	Mature
Water-soluble	Fertigation flexibility	Compatibility and precipitation	Mature
Suspension	Flexible nutrient loading	Settling and rheology	Established
Coated CRF	Extended release	Coating cost and soil sensitivity	Established
Stabilized N	Delays selected N reactions	Environment-dependent response	Established
Micronutrient chelates	Targeted availability	Cost and ligand stability	Established
Biodegradable coatings	Reduced polymer persistence	Release consistency, cost, biodegradation evidence	Emerging
Nano-enabled carriers	Targeted delivery; potentially lower rates	Particle fate, safety, cost, regulation	Emerging

^a Qualitative assessment by the authors of the evidence base and commercial adoption.

5. Biological Nutrient Sources and Biostimulants

Biological inputs complement rather than replace mineral fertilizers in most systems. Their performance depends on living or bioactive components whose viability, composition and interaction with the soil must be controlled through formulation and quality management (Table 4). Plant growth-promoting bacteria act through several mechanisms, including nitrogen fixation, phosphate solubilization, phytohormone production and the suppression of pathogens (Glick, 2012).

5.1. Biological nitrogen fixation

Biological nitrogen fixation by legume–rhizobia symbioses is a major biological N input to agriculture (Herridge et al., 2008). Associative and free-living diazotrophs such as *Azospirillum* and *Azotobacter* are widely marketed as inoculants for cereals and other non-legumes, although the magnitude and reproducibility of their contribution to crop N supply remain contentious. The role of microbiome-informed strain selection and engineering in improving this reproducibility has been reviewed elsewhere (Singh & Pandey, 2026d).

5.2. Phosphorus-mobilizing microorganisms

Phosphate-solubilizing bacteria and fungi release organic acids and phosphatases that can mobilize sparingly soluble inorganic and organic phosphorus (Rodríguez & Fraga, 1999; Richardson & Simpson, 2011). Solubilization on agar plates is, however, a poor predictor of plant response; evaluation requires soil-based assays and field trials that account for soil P status, pH and competition with native microbiota (Bashan et al., 2014).

5.3. Arbuscular mycorrhizal fungi

Arbuscular mycorrhizal fungi (AMF) extend the effective absorbing surface of roots and improve uptake of phosphorus and some micronutrients, with responses typically greatest in low-P soils (Smith & Read, 2008). Because AMF are obligate symbionts, commercial production relies on host-dependent culture systems, and inoculant quality depends on propagule density, viability and purity (Singh & Pandey, 2026e). Formulation, carrier choice, quality standards and shelf life are the main bottlenecks for field-ready products (Singh & Pandey, 2026a).

5.4. Biostimulants and microbial metabolites

Biostimulants are defined by their function—stimulating nutrition processes, nutrient use efficiency, abiotic stress tolerance or quality traits—rather than by nutrient content (du Jardin, 2015). Recognized categories include humic substances, protein hydrolysates, seaweed extracts and other biopolymers, and beneficial fungi and bacteria (Calvo et al., 2014; du Jardin, 2015; Rouphael & Colla, 2020). Microbial metabolites and fungal biomolecules have been proposed as defined-composition biostimulant and bioprotectant ingredients that may also support plant nutrition and stress resilience (Singh & Prasad, 2025; Singh & Pandey, 2026f, 2026g). Because product composition is often variable, chemical definition, bioassay-based standardization and crop- and environment-specific field testing are needed before efficacy claims are made (Rouphael & Colla, 2020).

5.5. Product quality and manufacturing

Productizing microbial biologicals requires fermentation scale-up, carrier selection, stability and shelf-life studies and manufacturing transfer (Bashan et al., 2014; Singh & Pandey, 2026h). Quality specifications should include viable counts at manufacture and at the end of shelf life, strain identity and absence of contaminants. In India, biofertilizers and, more recently, biostimulants have been brought within the Fertiliser (Control) Order framework through amendments; current schedules and specifications must be checked before registration (Government of India, 1985).

Table 4. Biological inputs relevant to crop nutrition: quality attributes and sources of response variability.

Input	Principal mechanism	Critical product-quality attributes	Main sources of response variability
N-fixing inoculants (e.g., <i>Rhizobium</i> , <i>Azospirillum</i> , <i>Azotobacter</i>)	Biological N fixation; phytohormone production	Viable count, strain identity, carrier, shelf life	Host–strain compatibility, soil N status, native populations, pH, drought
P-solubilizing microorganisms	Organic acid and phosphatase release; P mobilization	Viability; activity verified in soil, not only on agar	Soil P status and pH, competition with native microbiota
Arbuscular mycorrhizal fungi	Extended hyphal network; P and micronutrient uptake	Propagule density, spore viability, purity	Host dependency, soil P level, tillage, fungicide use
Biostimulants (microbial or non-microbial)	Stimulation of nutrient uptake, stress tolerance or quality	Defined composition or bioassay standardization	Crop stage, dose, environment
Biochar	Cation exchange, water retention, liming effect; nutrient carrier	Feedstock, pyrolysis temperature, ash and contaminant content	Soil type, application rate, aging in soil

Referred from Smith and Read (2008), Bashan et al. (2014), du Jardin (2015) and Lehmann and Joseph (2015).

6. Fertilizer Product Development and Optimization

A rational development pipeline begins with crop nutrient demand, soil constraints and a defined product claim. Candidate formulations should be screened for nutrient content, compatibility, storage behavior, physical integrity and manufacturability before pot and field testing. Design-of-experiments methods, including factorial and response-surface designs, allow efficient examination of coating loading, binder type, granule size, mixing conditions and drying temperature (Montgomery, 2017).

Go/no-go criteria should be prespecified: regulatory grade compliance, batch-to-batch nutrient assay, acceptable storage stability, consistent release characteristics and agronomic advantage at comparable nutrient rates. Pilot batches should be assessed independently of discovery batches to detect scale-dependent failures such as changes in granule density, coating uniformity or moisture content. Figure 2 summarizes this stage-gated framework.

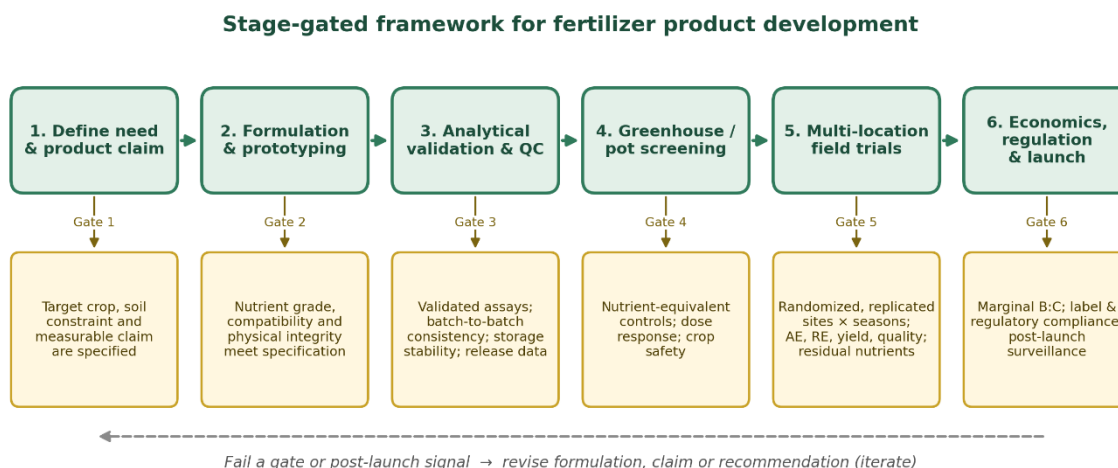


Figure 2. Stage-gated framework for fertilizer product development. Each stage ends in a gate with prespecified pass criteria; failure at a gate, or a post-launch performance signal, returns the product to formulation or claim revision. AE, agronomic efficiency; RE, apparent recovery efficiency; B:C, benefit–cost ratio; QC, quality control.

7. Physicochemical Characterization and Quality Control

Quality control should include validated nutrient assays, moisture, particle-size distribution, hardness, caking, solubility, suspension stability and product-specific release behavior. Nitrogen analysis must match the forms present (ammoniacal, nitrate, urea and, where relevant, slow-release N), and phosphorus and potassium methods must match the formulation matrix. Analytical validation should address specificity, precision, accuracy, recovery and measurement uncertainty. For microbial products, viable count, strain identity and contaminant limits are additional release criteria (Bashan et al., 2014; Singh & Pandey, 2026h).

Release studies should report medium composition, temperature, sampling schedule, mass balance and replicates. Release data are commonly fitted with first-order, Higuchi or Korsmeyer–Peppas models ($M_t/M_\infty = kt^n$) (Peppas, 1985; Ritger & Peppas, 1987); a good fit establishes a descriptive relationship but does not by itself establish the mechanism of control. In India, the relevant provisions of the Fertiliser (Control) Order and its current amendments must be checked for each grade, labeling requirement and analytical method (Government of India, 1985); a general reference to international methods is insufficient for regulatory conformity. Regulatory dossier preparation and harmonization across jurisdictions are discussed by Singh (2026).

For the Korsmeyer–Peppas expression, M_t is cumulative nutrient released at time t , M_∞ is the reference releasable amount, k is an empirical rate constant and n is the release exponent. Model fitting should specify the fitted release interval, sampling replication, uncertainty and assumptions; a fitted exponent does not independently establish a physical release mechanism. Extrapolation from water-release assays to soil conditions requires independent validation (Peppas, 1985; Ritger & Peppas, 1987; Shaviv, 2001).

8. Agronomic Evaluation and Field Trial Design

Replicated randomized block or factorial designs should compare a new product with nutrient-equivalent conventional fertilizers, a recommended-practice control and, where agronomically appropriate, a nutrient-omission treatment (Gomez & Gomez, 1984; Montgomery, 2017). Application timing, nutrient rate and irrigation must be documented. Multiple soils, locations and seasons are essential for generalizable recommendations.

Nutrient use efficiency is quantified with complementary indices (Baligar et al., 2001; Cassman et al., 2002; Fageria, 2009). Agronomic efficiency (AE), apparent recovery efficiency (RE), partial factor productivity (PFP) and physiological efficiency (PE) are given by:

$$AE = (Y_f - Y_0) / F \quad (1)$$

$$RE (\%) = 100 \times (U_f - U_0) / F \quad (2)$$

$$PFP = Y_f / F \quad (3)$$

$$PE = (Y_f - Y_0) / (U_f - U_0) \quad (4)$$

where Y_f and Y_0 are harvested yields with and without the focal nutrient, U_f and U_0 are the corresponding plant nutrient uptakes, and F is the amount of the focal nutrient applied, all in consistent units. Because $AE = (RE/100) \times PE$, a change in agronomic efficiency can be attributed to better recovery, better internal utilization, or both. The omission control (Y_0 , U_0) must isolate the nutrient of interest for these indices to be interpretable (Fageria, 2009).

For clarity, conventional internal efficiency is defined as $IE = Y_f / U_f$, whereas $PE = (Y_f - Y_0) / (U_f - U_0)$ is physiological (incremental) efficiency. Thus $AE = (RE/100) \times PE$, not $AE = (RE/100) \times IE$. All calculations require consistent nutrient units and an omission control that isolates the focal nutrient (Baligar et al., 2001; Fageria, 2009).

Trials should report yield with uncertainty, treatment-by-environment interaction, soil residual nutrients, crop quality and the marginal benefit–cost ratio. Mixed-effects models can account for location and season as random effects (Bates et al., 2015), and prespecified primary endpoints reduce selective reporting. Table 5 lists the minimum dataset recommended for multi-location trials.

Table 5. Minimum multi-location trial dataset.

Domain	Recommended observations
Site	Soil texture, pH, organic carbon, available nutrients, weather
Treatment	Grade, actual nutrient rates, application dates, placement
Crop	Stand, growth, tissue nutrient uptake, yield, quality
Environment	Residual soil nutrients; optional nutrient-loss measurements
Analysis	Variance components, uncertainty, treatment $\times$ site interaction
Economics	Incremental costs, returns, marginal benefit–cost ratio

9. Integrated Nutrient Management

Integrated nutrient management combines mineral sources, crop residues, manures, biological inputs and amendments according to their nutrient supply patterns. Organic amendments contribute to carbon cycling but have variable mineralization rates and cannot be assumed to replace mineral nutrient inputs at equal mass. Crop residue management in rice-based systems affects N immobilization and the recycling of P and K (Bijay-Singh et al., 2008). Biochar can improve cation exchange, water retention and nutrient retention, and can act as a nutrient carrier, but its effects depend strongly on feedstock, pyrolysis conditions, soil type and application rate (Lehmann & Joseph, 2015; Singh & Prasad, 2022). Balanced fertilization and the “right source, right rate, right time, right place” principles provide an operational framework (Fageria, 2009; Zhang et al., 2010; Bindraban et al., 2015).

A critical distinction is the difference between total nutrient content and plant-available nutrient supply. Manure and residue inputs differ in mineralization timing and may immobilize nitrogen temporarily, while microbial inoculants can be strongly conditioned by native soil populations and management. Accordingly, nutrient-equivalent comparisons should account for available nutrient fractions and background soil fertility; apparent benefits from combined inputs should not be attributed to biological synergy without factorial controls (Bijay-Singh et al., 2008; Bashan et al., 2014; Richardson & Simpson, 2011).

10. Crop Physiology and Crop-Specific Nutrient Management

Nutrient uptake and partitioning change from establishment through vegetative growth and reproduction. Crop-specific fertilizer programs should be based on soil testing, critical growth stages, tissue diagnostics and yield targets rather than universal grades. Cereals such as rice and wheat typically require substantial N during vegetative growth, whereas legumes obtain much of their N from fixation but depend on adequate P, K, S and micronutrient supply. Root traits, canopy development and stress responses determine whether an apparent deficiency reflects limited supply or impaired uptake (Marschner, 2012).

For rice, water regime and nitrogen placement influence volatilization and redox-mediated transformations; for wheat and maize, timing of nitrogen supply relative to canopy expansion and grain formation is important; and for legumes, symbiotic nitrogen fixation does not remove the need for adequate phosphorus, sulfur and micronutrients. These examples illustrate principles, not universal fertilizer prescriptions. Site-specific recommendations require soil testing, crop diagnostics and replicated field evaluation (Ladha et al., 2005; Fageria, 2009; Marschner, 2012).

Foliar and fertigation products require evaluation of concentration, crop safety, water quality, timing and interactions with other inputs. Chlorophyll meters and canopy reflectance indices can inform monitoring but are not unique indicators of nitrogen deficiency and should be calibrated for each crop and cultivar.

11. Emerging Technologies in Crop Nutrition

Precision agriculture combines soil maps, canopy sensing, yield history and weather information to adjust nutrient decisions in space and time (Gebbers & Adamchuk, 2010; Mulla, 2013). Machine-learning models are increasingly applied to yield prediction, nutrient-status estimation and decision support

(Liakos et al., 2018), and the integration of artificial intelligence, Internet-of-Things sensing and other computational approaches has been proposed to optimize water and fertilizer use (Singh & Singh, 2026) and to support the development of agricultural biologicals (Singh & Pandey, 2026c). Algorithms should be evaluated on independent farms and seasons, not only on calibration datasets. Formulation optimization can also use statistical learning, but process constraints and physical chemistry must remain explicit.

Biodegradable coatings, hydrogels, nano-enabled carriers and smart delivery systems are promising research areas. Their commercial value must be assessed against conventional fertilizers at equal nutrient inputs, including manufacturing energy, cost, field release consistency and environmental persistence (Chen et al., 2018; Kah et al., 2019; Lawrencina et al., 2021).

12. Commercialization, Product Life-Cycle Management and Technology Transfer

A product claim should be supported by a traceable chain from formulation specification to laboratory data, greenhouse screening, multi-location trials and economics. Technology transfer includes manufacturing tolerances, storage guidance, application recommendations and farmer-facing training. Post-launch surveillance should capture complaint patterns and performance across environments. Life-cycle assessment should account for raw materials, manufacturing energy, transport and field emissions, so that a gain in nutrient efficiency is not offset elsewhere in the chain (Chen et al., 2018).

Commercial readiness should also be evaluated through batch reproducibility, raw-material sourcing, energy and drying requirements, coating or granulation throughput, packaging and shelf-life performance. A product may demonstrate favorable nutrient release yet fail at pilot scale through abrasion, segregation, caking or inconsistent coating thickness. A formal stage gate should therefore document analytical compliance, process capability, agronomic effect size, cost sensitivity and regulatory pathway before launch (Trenkel, 2010; Montgomery, 2017; Lawrencina et al., 2021).

Claims such as higher yield, improved nutrient recovery or reduced leaching require outcome-specific evidence. A positive pot study or release curve alone is not sufficient for a field efficacy or environmental benefit claim. Table 6 & 7 summarizes the minimum evidence that should accompany common claims.

Table 6. Claim–evidence matrix for fertilizer product claims.

Product claim	Minimum supporting evidence	Evidence that is insufficient alone
Extended nutrient release	Validated release testing with stated medium, temperature, sampling schedule and mass balance; soil incubation for soil-applied claims	Single-temperature release curve in water without mass balance
Improved nutrient recovery	Uptake measured against nutrient-equivalent and omission controls at several sites	Pot study; yield data without uptake
Higher yield	Randomized, replicated multi-location trials over seasons; mixed-model analysis with effect sizes and uncertainty	Single-site, single-season trial
Reduced leaching or gaseous loss	Direct loss measurements (e.g., lysimeters, soil-water sampling, chambers) in relevant systems	Inference from a laboratory release curve
Biodegradable coating	Biodegradation tested under realistic soil conditions with defined endpoints and residue assessment	Laboratory compostability result alone
Economic benefit	Marginal benefit–cost ratio including product price, application cost and yield-value uncertainty	Yield increase alone

Table 7. Evidence priorities and limitations for crop nutrition technologies.

Technology	Most informative evidence	Key interpretation limitation
Coated fertilizers	Nutrient-equivalent multi-site uptake and yield; release in representative soils	Controlled release alone does not prove yield superiority
Stabilized nitrogen	N loss pathways plus yield across moisture and temperature regimes	Reducing one pathway can shift losses to another
Microbial inoculants	Strain identity, viability, soil-based efficacy and replicated field response	Plate solubilization does not establish field nutrient supply
Biodegradable coatings	Soil biodegradation endpoints, residues and life-cycle assessment	Bio-based composition does not prove biodegradation
Nano-enabled carriers	Independent field efficacy, exposure and environmental fate	Pot or laboratory response is insufficient for safety or efficacy claims
Precision nutrient management	Out-of-sample validation across farms and seasons	Calibration performance can overstate generalizability

13. Research Gaps and Future Perspectives

Priorities for research and development include:

- (i) crop-demand-matched release curves that account for temperature and moisture variability;
- (ii) standardized soil incubation protocols that link laboratory release to field supply;
- (iii) nutrient-equivalent, multi-location comparisons with transparent reporting of negative as well as positive trials;
- (iv) realistic biodegradation testing for bio-based coatings and assessment of coating residues in soil;
- (v) characterization of nutrient interactions in mixed grades and in combination with biological inputs;
- (vi) independent field validation of nano-enabled and data-driven technologies, including life-cycle and economic assessment; and
- (vii) cost-sensitive formulation design suitable for smallholder systems, supported by harmonized economic indicators.

A particularly useful research strategy is to test coating thickness $\times$ soil texture $\times$ irrigation regime as a factorial system while measuring nutrient release, plant uptake, yield and residual nutrient pools. Such designs can identify where coating technologies add value and where conventional split application remains preferable.

14. Conclusions

Crop nutrition innovation must connect mineral physiology, soil chemistry, product engineering, biological inputs and agronomic validation. The most credible products are not those with the most complex formulations but those with reproducible quality, appropriate nutrient timing, demonstrated crop value and acceptable environmental and economic outcomes. A stage-gated, crop-specific and multi-environment development process, together with explicit matching of claims to evidence, provides a defensible basis for specialty fertilizer commercialization.

Acknowledgments

The authors gratefully acknowledge the Head, Department of Biological Sciences, Rani Durgawati University, Jabalpur, Madhya Pradesh, India, for providing institutional facilities and support. The financial assistance received from the Council of Scientific and Industrial Research (CSIR), Government of India, is also sincerely acknowledged.

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