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# Beyond NPK: A Performance-First Critical Review of Secondary Nutrients, Micronutrients, and Multinutrient Slow-Release Fertilizers

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## Abstract

Conventional evaluations of slow- and controlled-release fertilizers frequently emphasize the release profile of a single nutrient despite the different chemical behavior and growth-stage requirements of nitrogen, phosphorus, potassium, secondary nutrients, and micronutrients. This critical review develops a performance-first interpretation of multinutrient fertilizers, connecting formulation architecture, nutrient-specific release, soil transformations, root-zone supply, crop demand, and environmental safety. This review assesses the literature corpus assembled from a structured set of topic-specific search strings as a critical narrative review rather than a systematic meta-analysis. Mechanistic evidence indicates that congruent multinutrient release should not be assumed from nominal NPK composition: differential dissolution, ion exchange, precipitation, transport, and biological transformations create distinct availability profiles. The review compares coated granules, mineral matrices, struvite-based materials, hydrogel systems, biochar composites, and micronutrient carriers, while identifying the limitations of short aqueous-release tests and single-element measurements. The paper proposes a conceptual multinutrient synchronization framework, a fast–slow–trace design portfolio, an evidence hierarchy, and nutrient-interaction assessments as research and product-development tools. These frameworks require independent validation across soils, crops, seasons, and industrial production conditions. The central conclusion is that effective multinutrient delivery depends on matching biologically useful supply vectors to crop demand within nutrient-specific safety and antagonism constraints, rather than uniformly slowing every ingredient.

**Keywords:** controlled-release fertilizer; multinutrient synchronization; secondary nutrients; micronutrient delivery; nutrient antagonism; crop nutrient-use efficiency

## Highlights

- Single-element release measurements do not establish multinutrient performance.
- Ca, Mg, S, and micronutrients require distinct delivery and safety profiles.
- Soil transformations and nutrient antagonisms control effective root-zone supply.
- A fast–slow–trace design and staged evidence framework are proposed.

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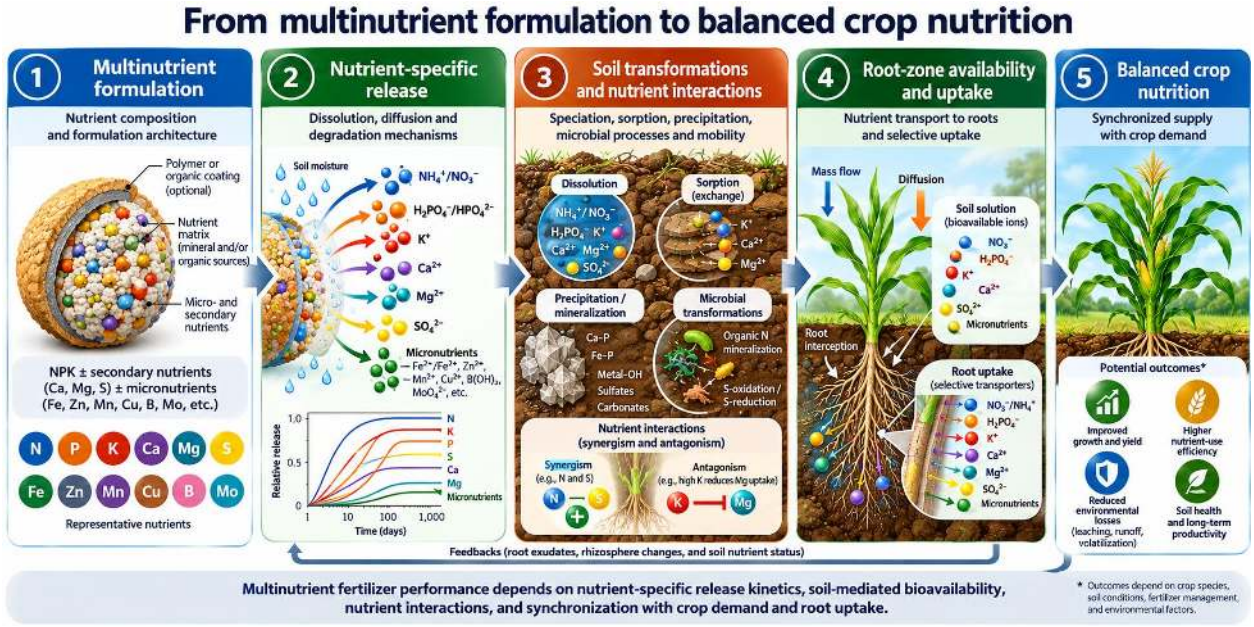
**Graphical Abstract**




## 1. Introduction: From Single-Nutrient Release to Nutrient Coordination

The scientific value of a slow-release formulation cannot be inferred from a prolonged nitrogen-release curve alone. Crops absorb a changing mixture of essential elements, whereas fertilizer materials undergo simultaneous dissolution, diffusion, redox transformation, exchange, and precipitation. Reviews of polymer coatings and controlled-release mechanisms explain how residence time can be manipulated, but do not establish that all nutrients remain agronomically synchronized (Lawrencia et al., 2021; Jariwala et al., 2022; Kassem et al., 2024).

Nitrogen, phosphorus, and potassium have different dominant loss pathways. Localized transport and tissue physiology constrain calcium supply; magnesium competes with other cations; sulfate can leach, while elemental sulfur requires oxidation; and Zn, B, Cu, and other micronutrients must remain within comparatively narrow effective dose windows. Consequently, a formulation can be nutritionally complete on the label but transiently unbalanced in the root zone (Ayamba et al., 2023; Beig et al., 2022).

This article's organizing hypothesis is that performance depends on coordination between nutrient-specific supply and crop demand, not on maximizing a generic slow-release duration. Figure 1 establishes the source-to-crop causal sequence, while Table 1 contrasts the

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dominant constraints. This framework treats proposed synchronization indicators as hypotheses to be validated, not established standards.

Unlike prior surveys of controlled-release materials and carbonaceous carriers, this review evaluates nutrient-resolved matching between effective root-zone supply and crop-stage demand, including secondary-nutrient constraints, micronutrient safety, and nutrient–nutrient antagonism. Recent reviews address sustainable multinutrient fertilizer technologies (Munjal et al., 2026), nano-enabled carrier design (Salimi et al., 2026), sustained-release environmental performance (Dhiman et al., 2026), and the need for standardized field and commercial validation (Maaz et al., 2025). These contributions motivate, but do not replace, the performance-first evidence framework advanced here. The present work does not claim to be the first review of multinutrient fertilizers.

Figure 1 distinguishes the measurable processes intervening between a fertilizer particle and plant acquisition.

**FORMULATION → NUTRIENT-SPECIFIC RELEASE → SOIL TRANSFORMATIONS → EFFECTIVE ROOT-ZONE SUPPLY → PLANT UPTAKE AND BALANCE**

**Figure 1.** Multi-nutrient fertilizer-to-crop continuum.
*Note.* Original conceptual figure developed for this review from the mechanistic topics synthesized in the cited literature.

The main implication is that an aqueous extraction profile is one measurement in a longer causal chain and cannot substitute for root uptake or nutrient balance.

**Table 1.** Nutrient-specific functions and constraints for formulation design

| Nutrient | Dominant physiological role | Key delivery constraint |
|---|---|---|
| **N** | Protein and canopy development | Temporal uptake and loss as $NH_3$, nitrate, or $N_2O$ |
| **P** | Root establishment and energy metabolism | Fixation, precipitation, and low diffusion |
| **K** | Osmotic regulation and crop quality | Exchange, cation competition, and stage demand |
| **Ca** | Cell walls and signaling | Local supply and transpiration-dependent movement |
| **Mg** | Chlorophyll and enzymes | K/Ca antagonism and solubility |
| **S** | Protein and N metabolism | Sulfate transport or elemental-S oxidation |
| **Zn/Fe/Mn/Cu** | Enzyme and redox function | pH, sorption, redox, and toxicity margins |
| **B/Mo** | Cell-wall and N metabolism | Crop-specific narrow dose windows and oxyanion |

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| | behavior |
|---|---|

*Note.* Qualitative synthesis; pathways differ with source chemistry, soil, crop, and application rate.

These constraints imply that the desirable release schedule for a given ion should be calculated based on its availability and uptake rather than copied from nitrogen kinetics.

### Evidence appraisal and limitations

The formulation literature spans coating technologies, mineral nutrient sources, and alternative carrier materials. These categories address different questions: coating studies focus on transport control, whereas mineral-source studies address dissolution and subsequent plant availability. Direct comparison therefore requires nutrient-resolved measurements rather than a shared slow-release designation. (Dida et al., 2024; Dovzhenko et al., 2024; Govil et al., 2024; Kalita et al., 2024; Li et al., 2022; Liu et al., 2026; Lu et al., 2022; Murugan et al., 2020; Pereira et al., 2021; Pereira et al., 2019; Siudak et al., 2026; Wu et al., 2022; Yu et al., 2022).

## 2. Review Methodology and Multinutrient Evidence Hierarchy

This critical narrative review evaluates a documentary corpus originally assembled using 13 topic-specific Boolean search blocks and the supplied bibliography of 143 works. A targeted bibliographic update was performed on 6 November 2026 to verify four additional relevant reviews and their publication metadata. The full historical search execution log, platform coverage, and original search dates were not supplied; accordingly, the 13 reproducible Boolean blocks presented in Appendix A are reconstructed search strategies rather than a retrospectively verified search log. The updated reference list contains 147 works. The review emphasizes 2020–2026, retains selected earlier mechanistic studies, and excludes preprints from its intended scope. DOI presence alone is not proof that all original 143 source records were independently resolved or verified. The review is critical and narrative; no PRISMA systematic-search completeness or meta-analytic claims are made.

Eligibility is interpreted mechanistically: included studies must illuminate a release mechanism, interacting nutrient chemistry, crop response, risk, or technology-readiness constraint. Publication-type and DOI screening alone are insufficient. In particular, classify a material with a prolonged urea release curve as single-nutrient evidence unless it quantifies nutrient release and plant uptake (Bi et al., 2020; Govil et al., 2024; Gutiérrez et al., 2022).

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Source appraisal distinguishes formulation/composition, single-element release, simultaneous multielement release, soil-mediated transformation, multi-element plant uptake, agronomic outcomes, and industrial/environmental confirmation. For comparisons, report initial elemental loading (mass), solution and residual-solid elemental inventories, recovery and balance closure, release medium and ionic strength, pH, temperature, moisture, duration, granule size, coating thickness/defects where relevant, and granule-to-granule variability. A percentage-release trajectory without nutrient-specific mass balances cannot establish coordinated release.

A seven-level evidence hierarchy is proposed: MN1, formulation and composition; MN2, element-specific release; MN3, simultaneous release of two or more nutrients; MN4, soil transformations and interactions; MN5, multi-element plant uptake; MN6, field yield, quality, and nutrient balance; and MN7, multi-season performance with industrial, cost, or environmental assessment. These stages are descriptors of evidence completeness, not formal technology readiness levels or a validated scoring instrument.

Figure 2 presents the intended progression of evidence completeness; a higher category denotes broader validation, not necessarily superior fertilizer performance.

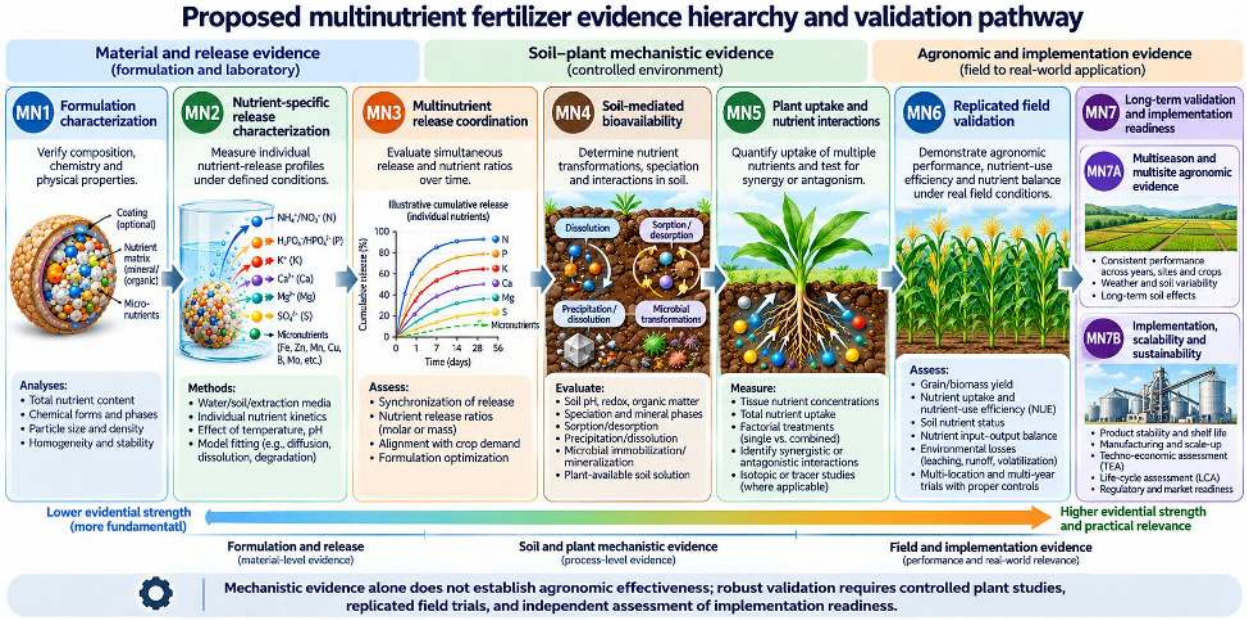


**Figure 2.** Proposed multinutrient evidence hierarchy and validation pathway.
*Note.* Original conceptual figure developed for this review; the MN hierarchy has not been externally validated.

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Transferability requires recording temperature, soil pH and texture, dose, irrigation, crop stage, extraction medium, and study duration. Comparisons without these contextual variables can invert apparent rankings among formulations.

**Evidence appraisal and limitations**

Reviews of nanostructured carriers help map candidate materials, but review-level coverage does not replace independent validation of simultaneous nutrient uptake. The MN classification is consequently a proposed reporting framework, not a quantitative ranking of efficacy. (Beig et al., 2022).

## 3. Nutrient-Specific Functions and Release Requirements

Nitrogen uptake can be strongly stage-dependent, and its useful release window must balance volatilization, nitrification, denitrification, and leaching. Phosphate requires early availability for growth but remains susceptible to immobilization; potassium often meets ongoing osmotic demand but competes with divalent cations. Mechanistic reviews report diverse coating materials and release models, yet it remains uncertain how single-ion mechanisms extend to multinutrient performance (Lawrencia et al., 2021; Abbas et al., 2022).

Secondary nutrients cannot be treated as passive additions. Calcium affects structural integrity and signal regulation; magnesium is central to chlorophyll-related metabolism and enzyme function; and sulfur connects sulfate nutrition with nitrogen assimilation. Their effective supply therefore depends on different dissolution and transport controls, even when formulated in the same granule. Micronutrients add another dimension because the interval between ineffective supply and undesirable accumulation may be limited.

For design, the relevant quantity is time-dependent plant-available supply, not the concentration of an element in bulk material. The difference should be explicitly characterized through root-zone extraction and tissue analysis rather than inferred from a total elemental assay.

**Evidence appraisal and limitations**

Nitrogen-release inhibitors and processed potassium minerals illustrate two non-equivalent strategies: delaying the availability of a soluble nutrient versus mobilizing a

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nutrient from a comparatively resistant source. The relevant endpoint differs accordingly, and bulk nutrient analysis cannot substitute for availability tests. (Gao et al., 2026; Pereira et al., 2019a; Pereira et al., 2019b; Pereira et al., 2019; Pereira et al., 2025; Pereira et al., 2026).

## 4. Secondary Nutrients: Ca, Mg, and S as Slow-Release Components

Gypsum, calcium phosphate, calcium silicates, magnesia, dolomite, and magnesium-bearing minerals illustrate how a nutrient can also function as a structural material. Mineral solubility, pH, reaction-product layers, and interparticle transport may govern nutrient release rather than polymer permeation. Struvite offers a particularly informative multiphase case because magnesium, ammonium, and phosphate are chemically coupled in a single crystalline compound (Iftikhar et al., 2024; Li et al., 2024).

Although struvite is often described as a slow-release fertilizer, the useful proportions of Mg, N, and P depend on soil dissolution and a particular crop's actual demand. Moreover, phosphorus can precipitate again after dissolution. Therefore, stoichiometric release from a mineral does not imply stoichiometric root acquisition. Biochar-loaded struvite products further introduce adsorption and desorption processes (Li et al., 2023; Li et al., 2024).

Elemental sulfur differs fundamentally from sulfate: microbial oxidation is required before sulfate nutrition becomes available. Sulfur-coated urea combines coating and nutritional functions, but coat integrity and oxidation do not translate into a predictable S supply schedule. The research priority is to report Ca, Mg, S, and associated N/P kinetics separately under soil conditions, followed by multi-element uptake.

### Evidence appraisal and limitations

The struvite-centered literature links crystallization and nutrient recovery to mineral dissolution, while phosphate composites and engineered carriers introduce separate controls on adsorption and diffusion. Recovery yield, release rate, and crop uptake are distinct outcomes; comparisons should specify which were actually measured. (Erro et al., 2024; Ghribi et al., 2026; He et al., 2022; Iftikhar et al., 2024; Inácio et al., 2025; Kallikazarou et al., 2025; Khan et al., 2025; Labbilta et al., 2020; Leon et al., 2024; Li et al., 2024; Li et al., 2023; Luu et al., 2025; Nazari et al., 2024; Piri et al., 2024; Ramut et al., 2025; Sharma et al., 2025; Wilson et al., 2025; Yan et al., 2025; Zhang et al., 2026; Zhou et al., 2024).

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## 5. Micronutrients: Controlled Delivery within a Narrow Agronomic Window

Micronutrient formulation is primarily a problem of safe local dosage and chemical speciation. Zn may precipitate or bind to oxides and clays; Fe is often limited by oxidation and alkalinity; Mn is redox-sensitive; Cu has a strong affinity for organic phases; B can show a narrow deficiency-toxicity interval; and Mo occurs predominantly as an oxyanion in relevant soil solutions. Treating all micronutrients as analogous divalent cations is chemically incorrect.

Clay-exchanged Zn and related nanostructured materials can alter the root's exposure history, but an attractive release curve alone cannot establish improved uptake or biological safety (Cyriac et al., 2024; Haydar et al., 2024; Beig et al., 2022). A complete experimental design requires dose-normalized comparisons, soil extraction, tissue nutrient levels, yield and quality, and residual inventory.

Multi-micronutrient carriers must additionally address competition for sorption and chelation sites, spatial segregation, and inadvertent release of co-loaded elements. Biofortification studies should distinguish greater tissue concentration from a favorable balance among essential nutrients and from toxicity risk. A formulation that reduces an acute deficiency may expose another limiting nutrient.

### Evidence appraisal and limitations

Micronutrient systems must be evaluated by soluble dose, chemical speciation, and tissue response. Evidence from a single element or carrier cannot be extrapolated automatically to simultaneous micronutrient supply because sorption competition and phytotoxicity thresholds vary among elements. (Akbarzadeh et al., 2024; Chu et al., 2024; Cyriac et al., 2024; Haydar et al., 2024; Huang et al., 2022; Ma et al., 2023; Mohanraj et al., 2024; Mohrazi et al., 2026; Sales et al., 2024; Thombare et al., 2021; Wei et al., 2026; Wu et al., 2024).

## 6. NPK Slow-Release Architectures

Coated granules, hydrogel matrices, organomineral systems, biochar/hydrochar composites, layered minerals, and hybrid inorganic–organic carriers offer different release controls. A membrane around a soluble NPK core does not necessarily retard N, P, and K in

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the same proportions, because their diffusion, dissolution, and subsequent soil immobilization differ. Biodegradable coating performance is therefore only one part of the product evaluation (Abbas et al., 2022; Bi et al., 2020; Kassem et al., 2024).

Hydrogels retain water and offer tunable transport but can exhibit chemistry-dependent swelling and nutrient desorption. Biochar-based carriers integrate pore adsorption, surface reactions, and soil conditioning, yet broad conclusions on nutrient efficiency require normalization by dose and soil properties (Das et al., 2023; Costa et al., 2026; Jia et al., 2021). Mineral K systems based on glauconite, feldspar, and muscovite may be valuable when dissolution matches crop demand, but mineral provenance and activation conditions strongly affect availability (Pereira, 2025; Pereira, 2026).

The central engineering trade-off is between a physically mixed formulation that can segregate during handling and a compound granule with greater chemical compatibility risks. Layered or compartmentalized designs may enable independently programmed delivery; however, they must be evaluated against real manufacturing complexity, storage stability, and uniformity across individual granules.

Figure 3 illustrates a possible alternative to equal retardation of all components: the fast–slow–trace portfolio.

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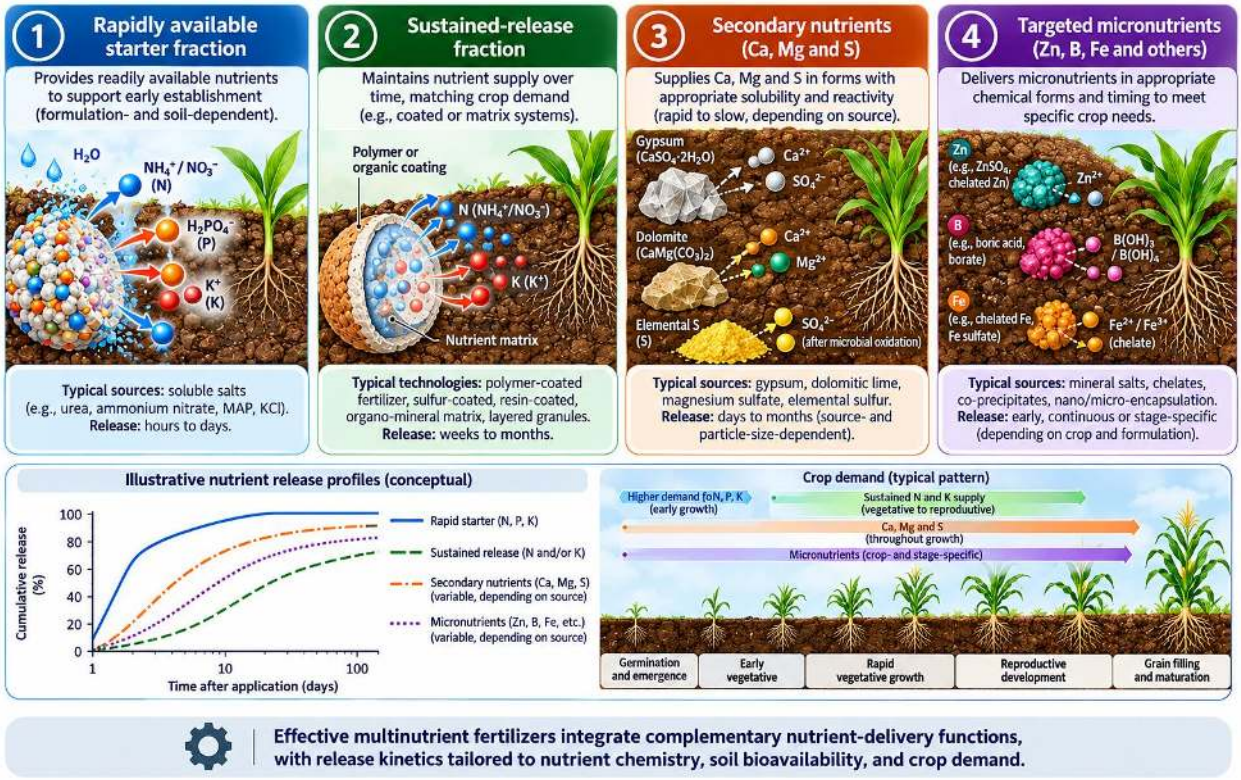


**Figure 3.** Conceptual fast–slow–trace multinutrient fertilizer architecture.
*Note.* Original conceptual figure; the proposed architecture requires experimental formulation and crop validation.

In this portfolio, a relatively fast starter fraction supports establishment, a durable reservoir supplies major macronutrients, and trace components are controlled separately within their safe windows. No single composition or release ratio is presumed universal.

**Table 2.** Mechanism-based comparison of multinutrient fertilizer architectures

| Architecture | Dominant control | Critical evidence gap |
|---|---|---|
| **Coated compound granule** | Coating transport and defect formation | Separate N/P/K release curves and granule variability |
| **Hydrogel or matrix** | Swelling, diffusion, matrix decay | Soil moisture and multinutrient uptake |
| **Struvite/mineral phase** | Dissolution and secondary precipitation | Joint Mg/N/P supply and P fate |
| **Biochar/hydrochar carrier** | Adsorption, desorption, and soil buffering | Net benefit relative to nutrient-equivalent controls |
| **Clay/zeolite carrier** | Ion exchange and surface competition | Competing K/$NH_4$/Zn release |
| **Layered/compartmentalized** | Sequential barrier exposure | Manufacturing quality and multiseason field performance |

*Note.* Original mechanism-based comparison derived from the cited literature; the classifications do not rank commercial readiness.

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Comparative evidence is strongest when products use the same nutrient dose, particle size range, soil, and crop.

**Evidence appraisal and limitations**

The reviewed carrier classes differ in permeability, erosion, biodegradation, and manufacturing requirements. As a result, prolonged aqueous release alone cannot distinguish a broadly useful agronomic product from a coating that merely delays nutrient transfer under a particular test condition. (Abbas et al., 2022; Das et al., 2023; Nascimento et al., 2022; El-Aziz et al., 2022; Ghobashy et al., 2024; Gomez-Maldonado et al., 2024; Guo et al., 2026; Han et al., 2020; Hidayat et al., 2026; Inphonlek et al., 2023; Jia et al., 2021; Karmil et al., 2025; Kassem et al., 2024; Lei et al., 2026; Liu et al., 2024; Mandal et al., 2025; Mansouri et al., 2023; Mihok et al., 2020; Nascimento et al., 2026; Pereira, 2026b; Piash et al., 2022; Rafique et al., 2025; Ramesh et al., 2024; Palacios et al., 2025; Ravindran et al., 2025; Riseh et al., 2023; Seddighi et al., 2024; Song et al., 2024; Suwardi et al., 2024; Tan et al., 2025; Tang et al., 2026; Wang et al., 2022; Wang et al., 2023; Yang et al., 2025; Yi et al., 2026).

## 7. Multinutrient Release Mechanisms and Stoichiometric Mismatch

Release can be congruent at the solid surface yet incongruent at the root. Dissolution, diffusion, cation exchange, coating degradation, competitive complexation, and precipitation may operate in parallel. Thus, treat the measured aqueous release ratio and the resulting bioavailable ratio as distinct observables. The limitation is particularly acute when a trial measures only total N or total P in leachate (Dida et al., 2024; Li et al., 2024).

A useful conceptual descriptor for nutrients i and j is $M_{ij}(t) = [S_i(t)/S_j(t)]/[D_i(t)/D_j(t)]$, where S is effective root-zone supply rate, and D is crop demand rate in consistent mass-per-area-per-time units. A value near unity indicates ratio agreement only when all four terms are positive and accurately observed; it does not by itself demonstrate that absolute supplies are sufficient. The indicator has not been validated and is not an established agronomic index.

Ratio concordance should be paired with an independently assessed absolute sufficiency test: $S_i(t) \geq D_{i,\min}(t)$ within a biologically justified growth interval, with both quantities expressed on the same nutrient-mass, area and time basis. Here $D_{i,\min}$ denotes a crop- and stage-specific minimum effective supply requirement rather than a universal

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threshold. This condition is a proposed analytical safeguard, not a validated agronomic criterion. Cases with zero demand or supply require separate treatment because the ratio indicator is undefined.

In practice, matched dissolution experiments must include elemental inventories, recovered liquid and solid masses, changing solution pH, and soil fixation measurements. Without a complete elemental balance, apparent slow release may conceal sorption, precipitation, or analytical loss. Multiple nutrient trajectories are therefore more informative than an aggregate percentage of nominal NPK released.

**Evidence appraisal and limitations**

Dissolution chemistry, diffusion geometry, and the extraction medium influence reported nutrient-release profiles. Claims of coupled release require measurements for each intended component over the same interval and under explicitly described conditions. (Bi et al., 2020; Costa et al., 2026; Hameed et al., 2024; Lawrencia et al., 2021; Liu et al., 2022; Liu et al., 2023; Pereira, 2025b; Sun et al., 2024).

## 8. Nutrient–Nutrient Interactions and Antagonisms

Direct competition and indirect chemical transformations link nutrient fates. Elevated K can suppress Mg or Ca acquisition; phosphate may alter Zn and Fe availability; $NH_4^+$ can compete for exchange sites; and P may precipitate with Ca or Mg under suitable conditions. Sulfur and nitrogen metabolism are linked; boron–calcium responses are tissue-specific. Interpret these patterns as conditional rather than universal antagonisms (Ayamba et al., 2023; Aquino et al., 2025).

Interactions exist at three scales: within the granule (chemical incompatibility), within the soil (exchange, sorption, precipitation, redox), and within the crop (competitive uptake and metabolic coupling). Accordingly, a formulation with correct elemental content may still deliver an imbalanced nutrient exposure. Figure 4 identifies the principal interaction groups that should be tested explicitly.

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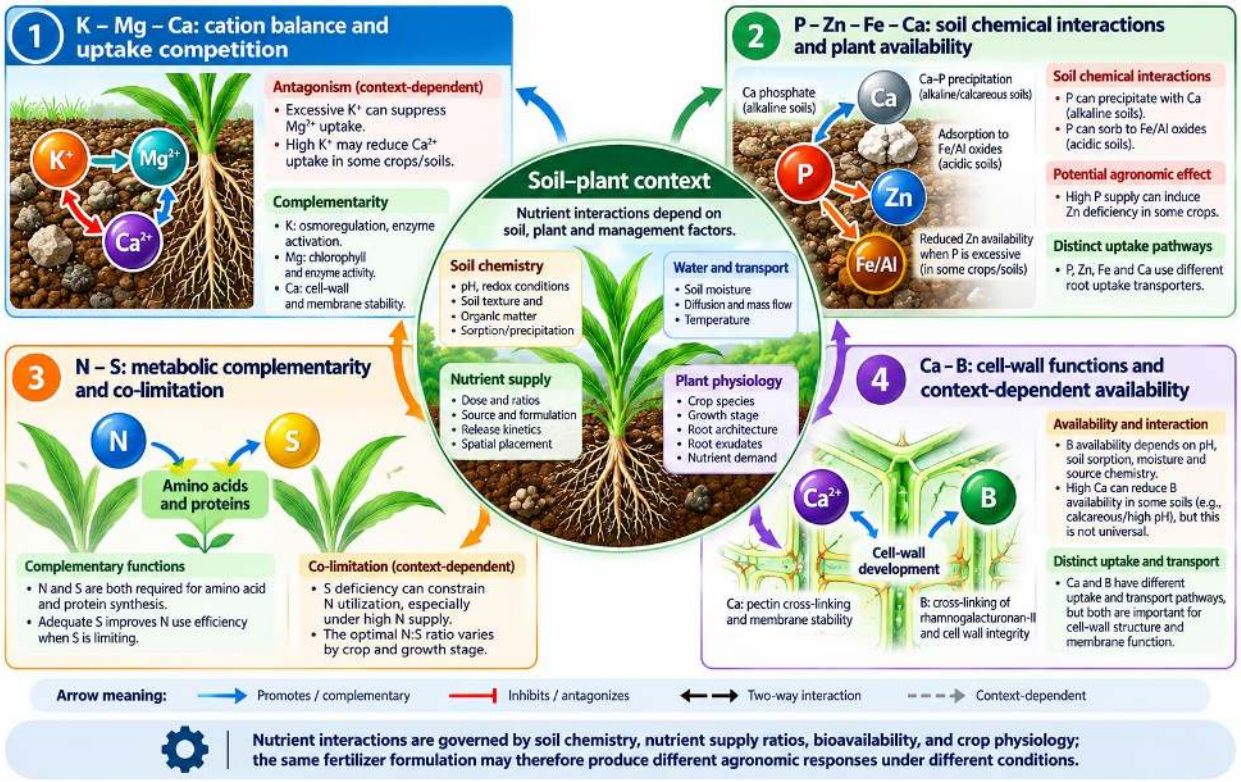


**Figure 4.** Selected interacting nutrient pairs and groups.
*Note.* Original conceptual scheme; arrows denote interactions requiring context-specific testing, not fixed antagonistic coefficients.

A useful evaluation pairs single-omission nutrient treatments with full NPK+ formulations, measuring tissue ratios and root-zone inventory. This identifies whether yield gains result from coordinated release or simply correcting the originally limiting nutrient.

**Table 3.** Critical interaction matrix for multinutrient formulation assessment

| Interaction | Possible mechanism | Suggested verification |
|---|---|---|
| **K–Mg / K–Ca** | Cation exchange and root uptake competition | Tissue ratios, exchangeable soil pools |
| **$NH_4$–K** | Shared exchange sites and uptake pathways | Solution profiles and exchange capacity |
| **P–Zn / P–Fe** | Sorption, precipitation, and physiological effects | Soil speciation and tissue concentration |
| **P–Ca / P–Mg** | Mineral precipitation or dissolution | Solid-phase identification and extraction |
| **N–S** | Metabolic coordination | N/S tissue content and protein quality |
| **Ca–B** | Structural and developmental interaction | Tissue distribution and reproductive response |

*Note.* Qualitative hypotheses; the direction and magnitude depend on fertilizer dose, soil, and crop.

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Interaction matrices should therefore serve as experimental checklists rather than universal numerical adjustment factors.

**Evidence appraisal and limitations**

Evidence on nutrient interactions links chemical compatibility in the formulation with soil exchange and physiological competition. Associations observed under one fertilizer regime may change with dose, soil properties, and crop demand; such heterogeneous studies do not support a universal antagonism coefficient. (Ayamba et al., 2023; Fang et al., 2024; Huang et al., 2025; Liu et al., 2025; Luo et al., 2024; Singh et al., 2024; Wang et al., 2023; Yang et al., 2026).

## 9. Soil-Controlled Multinutrient Availability

Soil pH changes phosphate fixation, metal hydrolysis, micronutrient sorption, and dissolution of Ca- or Mg-bearing minerals. Cation-exchange capacity modifies K, $NH_4$, Ca, Mg, Zn, and Cu retention. Redox alters Fe, Mn, and S chemistry, while carbonate buffering, organic ligands, microbial transformations, root exudates, ionic strength, and water content impose further controls (Aquino et al., 2025; Ayamba et al., 2023).

Soil context frequently changes the apparent ranking of formulations: a material that releases nutrients gradually into deionized water may release or immobilize them differently in acidic, calcareous, saline, or intermittently saturated soil. This difference precludes inference of field nutrient delivery from a generic dissolution percentage. Comparative studies should include at least one representative soil from each intended application environment.

An informative protocol measures porewater and exchangeable pools, speciation-sensitive extractions, mass balance, microbiological change where relevant, and plant acquisition. The target is a temporally resolved effective supply vector rather than a one-time extraction.

For formulations proposed for broad use, an initial transferability matrix should, where agronomically relevant, include (i) acidic, highly weathered soil, (ii) neutral or moderately buffered soil, and (iii) calcareous or alkaline soil. Record soil texture, cation-

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exchange capacity, organic matter, carbonate status, redox regime, moisture, and salinity as applicable. These classes are a proposed testing design, not universal mandatory categories.

**Evidence appraisal and limitations**

The soil-focused literature covers microbial responses, amendments, and composite fertilizer behavior. These sources motivate including soil pH, buffering, and microbial activity in evaluation protocols, but they do not establish a common response across soils. (Aquino et al., 2025; Arafa et al., 2022; Chen et al., 2026; El-Gharabawy et al., 2025; Gao et al., 2025; Rashid et al., 2025; Singh, 2025; Toda et al., 2023; Xiang et al., 2023).

## 10. Multinutrient Crop-Demand Synchronization

Crop demand is both temporal and stoichiometric. Early root establishment can require immediately available P and trace elements, while canopy growth raises N requirements and later reproductive phases may alter K, S, and micronutrient demand. Even a constant total fertilizer-release rate can therefore produce a changing mismatch with demand. The benchmark should be growth-stage-specific supply, not a constant formulation ratio.

For each essential nutrient i, define an illustrative integrated mismatch as $E_i = \int|S_i(t) - D_i(t)|dt / \int D_i(t)dt$ across the chosen crop period, provided the denominator is positive, and both quantities use the same units. A multinutrient mismatch could be expressed as $\Sigma\, w_i E_i$ for transparent, crop-relevant weights $w_i$. These equations are proposed analytical tools; they have not been calibrated or validated for cross-crop rankings.

For any numerical application, the integration interval $[t_0, t_1]$ must correspond to a specified crop-development period; $D_i(t)$ must be estimated from crop-stage nutrient accumulation and physiological uptake data, while $S_i(t)$ requires soil-calibrated root-zone availability and flux measurements rather than direct substitution of deionized-water release rates. Where a weighted aggregate $\Sigma_i w_i E_i$ is used, weights must be declared and justified by crop-specific limitation or environmental risk; uncertainty and sensitivity to plausible weights, demand trajectories, and supply estimates must be reported. None of these proposed indicators is an established validation standard.

The framework clarifies why a design can be optimized through staged delivery rather than by attempting identical kinetics for every ion. It also exposes the need for spatially

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resolved measurements: the fertilized microzone, rhizosphere, and bulk soil can differ markedly. Nutrient demand estimates require biomass accumulation and stage-specific elemental uptake, not yield endpoints alone.

**Evidence appraisal and limitations**

Crop-specific nitrogen synchronization studies provide useful designs for testing supply–demand matching. They cannot, by themselves, validate a multinutrient mismatch index without simultaneous measurements of the other intended nutrients. (Liu et al., 2025; Ma et al., 2026; Junior et al., 2026; Xiao et al., 2026).

## 11. From Multinutrient Release to Agronomic Performance

Agronomic validation requires measurement of at least two, and ideally all intended, nutrients in tissue and soil pools, alongside yield, quality, nutrient-use efficiency, and residual fertility. A reported yield increase without an appropriate nutrient-equivalent conventional control does not reveal whether release synchronization was beneficial. Reported improvements can also reflect water retention, soil pH adjustment, or a higher effective dose rather than controlled release itself (Costa et al., 2026; Jia et al., 2021).

Causal comparison requires a conventional fertilizer control delivering equivalent elemental doses, with nutrient-by-nutrient normalization across test and control treatments. Single-nutrient omission treatments, when feasible, help separate correction of an initially limiting deficiency from gains specifically attributable to coordinated delivery. Measurements should include multi-element tissue acquisition and ratios, yield and quality, soil residual pools, and potential deficiency and toxicity symptoms; improved yield by itself does not demonstrate nutrient synchronization.

Biofortification with Zn or Fe adds a product-quality dimension, but evaluate the response alongside crop yield, nutrient interactions, and safety margins. For N–S systems, protein quality may be an appropriate endpoint; for K, quality and water relations may be important. Multiple seasons and contrasting soils are necessary before broad claims of superiority.

Table 4 identifies minimum evidence at laboratory, pot, and field scales, while acknowledging that no single test covers the full multinutrient system.

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**Table 4.** Minimum measurements for escalating multinutrient evidence

| Scale | Measurements | Critical failure mode |
|---|---|---|
| **Formulation laboratory** | Composition, distribution, strength, separate ion release | Nominal composition mistaken for joint release |
| **Soil incubation/column** | Time-resolved porewater and solid pools, mass balances | Dissolution mistaken for availability |
| **Pot/greenhouse** | Tissue uptake of multiple nutrients, yield, safety | Single nutrient response dominates attribution |
| **Field** | Nutrient-equivalent controls, yield, quality, losses | Spatial/seasonal variability ignored |
| **Multiseason / industrial** | Manufacturing, storage, TEA, LCA, soil legacy | Insufficient durability and scale transfer |

*Note.* Original proposed measurement checklist; not an established formal standard.

A claim of improved balanced nutrition should be withheld when only one nutrient or one growth endpoint has been measured.

### Evidence appraisal and limitations

The field and pot literature emphasizes distinct response variables, including yield, plant uptake, soil residual nutrients, and environmental losses. A claim of balanced nutrition requires a multidimensional comparison rather than interpreting an isolated yield increase as evidence of full nutrient synchronization. (Channab et al., 2024; Dere et al., 2025; García-Ilizaliturri et al., 2025; He et al., 2025; Ho et al., 2025; Jiang et al., 2024; Manzoor et al., 2022; Motamedi et al., 2023; Ren et al., 2025; Ren et al., 2026; Sharma et al., 2025; Valle et al., 2023; Xu et al., 2023; Zheng et al., 2026).

## 12. Environmental Performance, Manufacturing, Economics, and Scale-Up

The environmental evaluation must distinguish ammonia loss, nitrate leaching, nitrous oxide, phosphate transport, sulfate leaching, micronutrient accumulation, and unintended residues from coatings or nano-enabled carriers. Lower nutrient concentration in one leachate sample is not equivalent to reduced cumulative impact. Biodegradable or bio-based materials also require assessment of manufacturing inputs and degradation products (Jariwala et al., 2022; Chojnacka et al., 2020; Gutiérrez et al., 2022).

In process engineering, nutrient density, granule uniformity, coating defects, dust, hygroscopicity, and storage stability jointly affect commercial feasibility. Each additional nutrient or delivery compartment increases mixing, granulation, and quality-control complexity. Economic assessment should be normalized to crop-relevant performance—such

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as cost per unit of incremental harvested yield or corrected nutrient deficiency—not solely to cost per tonne of fertilizer.

A credible techno-economic assessment requires defined throughput, raw material specification, yields, energy, drying, waste handling, and product acceptance criteria. Life-cycle assessment also requires explicit system boundaries, a functional unit, coating fate, the agronomic use phase, and sensitivity analysis. These should not be inferred from small-batch laboratory demonstrations (Govil et al., 2024; Beig et al., 2022).

Minimum techno-economic reporting should specify plant throughput, raw-material sourcing and costs, granulation/coating/matrix processing, drying energy, recycle and rework, reject rates, packaging, storage stability, quality control, nutrient mass delivered, and cost per incremental crop-output unit relative to nutrient-equivalent conventional controls. Environmental accounting should distinguish $NH_3$, $NO_3^-$, $N_2O$, P transport, sulfate losses, micronutrient accumulation, carrier/coating residues, and life-cycle boundaries.

**Evidence appraisal and limitations**

Environmental reviews and material-development papers cover different levels of readiness. Distinguish demonstrated release kinetics from a complete manufacturing, environmental, or economic appraisal, particularly when carrier production and end-of-life impacts remain unmeasured. (Chojnacka et al., 2020; Eddarai et al., 2024; Gutiérrez et al., 2022; Jariwala et al., 2022; Pereira, 2025a; Pereira, 2026a; Pereira, 2026c; Witt et al., 2024; Ye et al., 2020; Yetilmezsoy et al., 2024).

## 13. Critical Synthesis, Design Rules, and Conclusions

The reviewed mechanisms support a shift from fixed-composition multinutrient fertilizer to programmed delivery. A defensible candidate formulation should begin with a crop–soil deficiency diagnosis, set nutrient-specific effective supply targets, select mineral and carrier phases by mechanism, and validate individual and simultaneous release before claiming balanced performance. The fast–slow–trace portfolio is a flexible design proposition rather than a prescription applicable to all crops.

The proposed hierarchy also reveals an evidence gap: materials development often outpaces multi-element soil and plant measurements. Future studies should compare

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complete mass balances, antagonist responses, micronutrient safety, multiseason crop performance, and manufacturing variability. Release synchronization should be tested against nutrient-equivalent standard practice to separate delivery-kinetics effects from dose correction.

The main conclusion is that a multinutrient fertilizer is effective only if distinct nutrient supply pathways collectively meet crop requirements without creating harmful imbalance. Neither a prolonged nitrogen-release curve nor a more complex composition independently establishes this outcome. Mechanism-resolved validation, soil-specific availability, and balanced uptake are necessary to translate advanced NPK+ formulations into reliable agronomic and environmental benefits.

## Declarations

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### Conflict of Interest

The author declares no conflict of interest.

### Data Availability

No new experimental datasets were generated. All quantitative values discussed in the review are traceable to the cited literature.

### Author Contributions

The author performed conceptualization, critical analysis, literature synthesis, visualization, and manuscript preparation.

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**Appendix A. Reconstructed topic-specific Boolean search strategies**

The following 13 strings are transparent, reproducible reconstruction aids for future searches, not a claim that the exact historical query log has been recovered. Suggested filters: peer-reviewed publications, 2020–2026; expand backward for seminal mechanistic evidence when justified. Adapt database syntax as needed. The targeted reference update date was 6 November 2026.

**A1. Fertilizer architectures.** ("slow-release fertilizer" OR "controlled-release fertilizer") AND (multinutrient OR "multi-nutrient") AND (coating OR matrix OR granule)

**A2. Nutrient-specific release.** (fertilizer AND ("element-specific release" OR "nutrient release kinetics")) AND (nitrogen OR phosphorus OR potassium)

**A3. Secondary nutrients.** ("slow-release fertilizer" OR "nutrient delivery") AND (calcium OR magnesium OR sulfur OR sulphur)

**A4. Struvite and phosphates.** (struvite OR "magnesium ammonium phosphate") AND (fertilizer OR soil) AND (dissolution OR uptake)

**A5. Micronutrient carriers.** ("controlled release" OR "slow release") AND (zinc OR iron OR manganese OR copper OR boron OR molybdenum) AND fertilizer

**A6. Hydrogels and matrices.** (hydrogel OR "polymer matrix") AND fertilizer AND (release OR uptake)

**A7. Carbonaceous carriers.** (biochar OR hydrochar) AND fertilizer AND (nutrient OR sorption OR release)

**A8. Clays and zeolites.** (zeolite OR clay OR layered) AND (fertilizer OR nutrient) AND (exchange OR release)

**A9. Nutrient antagonism.** (fertilizer OR crop) AND ("nutrient antagonism" OR "nutrient interactions" OR "cation competition")

**A10. Soil transformation.** ("fertilizer release" OR "nutrient availability") AND (soil pH OR redox OR precipitation OR sorption)

**A11. Crop-demand synchronization.** (fertilizer AND ("crop demand" OR "nutrient synchronization")) AND (uptake OR growth stage)

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**A12. Agronomic and environmental evidence.** ("controlled-release fertilizer" OR "multinutrient fertilizer") AND (field OR yield OR leaching OR emissions)

**A13. Scale-up and techno-economics.** (fertilizer AND (manufacturing OR scale-up OR techno-economic OR lifecycle OR commercialization))