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## Smart fertilizers for sustainable crop production, mechanisms, efficiency gains and unresolved trade-offs

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### Abstract

Fertilizer use efficiency remains one of the most persistent inefficiencies in global crop production, with a substantial fraction of applied nitrogen, phosphorus and potassium lost to leaching, volatilization, fixation or runoff before uptake. Smart fertilizers, encompassing nanoscale nutrient carriers, polymer and biochar coated controlled release formulations and microbially mediated nutrient delivery systems, have been proposed as a route to narrow this gap between applied and absorbed nutrients. Nanoscale carriers alter nutrient solubility and root surface interaction in ways that conventional granular fertilizers cannot replicate, yet the agronomic gains reported across pot and field trials become inconsistent once crop type, soil texture and nanoparticle chemistry are accounted for. Controlled release coatings achieve more predictable nitrogen release curves but carry cost and biodegradability concerns that limit smallholder adoption, particularly across South Asian cropping systems. Biofertilizer consortia offer a biologically grounded alternative, yet their field performance is highly sensitive to native soil microbiota and climatic variability, a dependency rarely acknowledged in comparative efficiency claims.

**Keywords:** Smart fertilizers, nanofertilizers, controlled release fertilizers, nutrient use efficiency, biofertilizers, sustainable crop production

### Introduction

Global nitrogen use efficiency in cereal systems rarely exceeds fifty percent, and in flood irrigated rice systems typical of the Indo-Gangetic plain the proportion of applied nitrogen actually recovered in grain and straw can fall well below that figure, the remainder lost through ammonia volatilization, nitrate leaching, denitrification and surface runoff (Trenkel, 2010) [17]. Phosphorus behaves rather differently, forming insoluble complexes with calcium, iron and aluminium within days of application, so that even where losses to water bodies are modest, the nutrient becomes agronomically unavailable rather than physically lost (DeRosa *et al.*, 2010) [4]. These inefficiencies are not new observations; they have shaped fertilizer research for decades, yet the response of the agrochemical industry until relatively recently was confined largely to adjusting application timing and split dosing rather than redesigning the fertilizer itself. Smart fertilizers depart from that pattern. The term is used here, following Liu and Lal (2015) [8] and Chhipa (2017) [3], to describe any formulation engineered so that nutrient release, solubility or bioavailability is decoupled from the passive dissolution kinetics of a conventional granule, whether through nanoscale particle engineering, polymer or mineral coatings that regulate diffusion, or microbial inoculants that convert or mobilise nutrients already present in soil. The appeal of this framing is that it groups technologies with genuinely different chemistries under a shared agronomic objective, narrowing the gap between the nutrient applied and the nutrient absorbed. The risk is that the framing can flatten real differences in maturity, cost and evidentiary strength between these technologies. Nanofertilizers remain, by and large, a laboratory and pot trial phenomenon, with field scale validation still comparatively thin (Raliya *et al.*, 2018; Kah *et al.*, 2018) [12, 6]. Controlled release fertilizers, by contrast, have decades of commercial history in horticulture and turf management, and their release kinetics are comparatively well characterised (Shaviv, 2001; Azeem *et al.*, 2014) [13, 2]. Biofertilizers sit somewhere between the two, agronomically familiar yet mechanistically variable, their performance contingent on native soil microbial communities in a way that neither

nanofertilizers nor coated fertilizers are (Adesemoye and Kloepper, 2009; Vejan *et al.*, 2016) <sup>[1, 18]</sup>. This review treats the three streams not as a checklist of interchangeable options but as overlapping, sometimes competing, solutions to the same efficiency problem, and asks where the comparative evidence genuinely supports one approach over another and where enthusiasm has outpaced field validation.

### Nanofertilizers and Nanoscale Nutrient Delivery

The mechanistic case for nanofertilizers rests on surface area and solubility behaviour that bulk fertilizer granules cannot achieve. Reducing a nutrient carrier to particles in the tens to low hundreds of nanometre range increases the proportion of atoms exposed at the particle surface, which in turn increases dissolution rate and, for micronutrients such as zinc and iron, improves diffusion toward root surfaces before fixation reactions in the rhizosphere can immobilise them (DeRosa *et al.*, 2010; Monreal *et al.*, 2016) <sup>[4, 9]</sup>. This is a genuinely distinct mode of action from a coated granule, whose release is governed by diffusion through an outer barrier rather than by particle scale solubility. Where the two technology streams converge, and where confusion in the literature often follows, is in formulations that combine nanoscale carriers with a slow release matrix, blurring the line between what counts as a nanofertilizer proper and what is simply a conventionally coated fertilizer loaded with nano-scale active ingredient (Subramanian *et al.*, 2015) <sup>[15]</sup>.

Zinc oxide and iron oxide nanoparticles have received the most sustained agronomic attention, largely because zinc and iron deficiency in cereal grain is widespread across calcareous and alkaline soils typical of much of the Indo-Gangetic plain. Foliar application of zinc oxide nanoparticles has produced grain zinc enrichment and modest yield gains in wheat and rice under several trial conditions (Raliya *et al.*, 2018) <sup>[12]</sup>, and Zulfiqar *et al.* (2019) <sup>[19]</sup> catalogue comparable responses across a wider set of crops including maize and tomato. What is less often acknowledged is how variable these responses are once soil zinc status, application method and particle coating chemistry are held up against one another. Trials conducted on already zinc

responsive soils tend to report larger relative gains than those conducted on soils with adequate native zinc, a distinction that is not always disclosed clearly in the abstracts of the primary studies, and this selective reporting inflates the apparent generality of the technology.

A second point of disagreement concerns whether nanoscale delivery genuinely improves nutrient use efficiency or whether it mainly improves the efficiency of application, meaning less material is needed to achieve the same tissue concentration, without necessarily improving the proportion of applied nutrient recovered by the plant. Kah *et al.* (2018) <sup>[6]</sup> draw this distinction explicitly and argue that much of the literature reporting nanofertilizer superiority has not run the appropriate mass balance comparisons against conventional fertilizer applied at agronomically equivalent, rather than numerically equal, rates. Guo *et al.* (2018) <sup>[5]</sup> reach a more favourable conclusion, reporting that nano-enabled formulations can reduce total nutrient loading by twenty to thirty percent while maintaining yield, though the trials underpinning that estimate are drawn overwhelmingly from controlled pot and greenhouse conditions rather than open field systems where leaching, runoff and soil heterogeneity complicate the picture considerably.

Toxicological uncertainty compounds the efficiency question. Several nanoparticle formulations, particularly those based on silver, copper or titanium dioxide, have shown phytotoxic or soil microbial community effects at concentrations not far above those proposed for agronomic use (Kah *et al.*, 2019) <sup>[6]</sup>. This does not invalidate the technology, but it does mean that dose-response curves for nanofertilizers cannot simply be extrapolated from the dose-response curves of their bulk counterparts, since nanoscale particles interact with cell membranes and microbial biofilms through mechanisms unrelated to nutrient solubility. Preetha and Balakrishnan (2017) <sup>[11]</sup> note that the regulatory and safety data required to register a nanofertilizer for commercial release in most jurisdictions, including India, remain underdeveloped relative to the pace of laboratory publication, a gap that is arguably the single largest constraint on translating nanofertilizer research into field-deployable products.

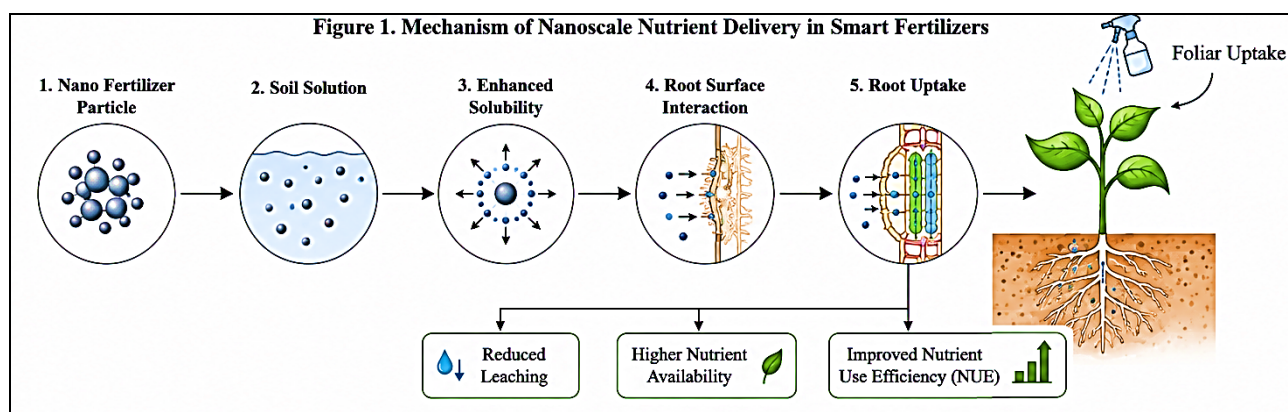


**Fig 1: Mechanism of Nanoscale Nutrient Delivery in Smart Fertilizers**

**Table 1:** Reported agronomic responses to nanoscale fertilizer carriers across crop species, synthesised from independent trials

| Nutrient carrier                                | Crop                                   | Application method        | Reported yield response                              | NUE or uptake indicator                               | References                                       |
|-------------------------------------------------|----------------------------------------|---------------------------|------------------------------------------------------|-------------------------------------------------------|--------------------------------------------------|
| Zinc oxide nanoparticles                        | Wheat ( <i>Triticum aestivum</i> )     | Foliar spray              | 6 to 12 percent grain yield increase                 | Grain zinc concentration raised 20 to 40 percent      | Raliya <i>et al.</i> , 2018 <sup>[12]</sup>      |
| Zinc oxide nanoparticles                        | Rice ( <i>Oryza sativa</i> )           | Foliar spray at tillering | Modest, site dependent                               | Grain zinc enrichment more consistent than yield gain | Zulfiqar <i>et al.</i> , 2019 <sup>[19]</sup>    |
| Iron oxide nanoparticles                        | Maize ( <i>Zea mays</i> )              | Soil application          | Up to 8 percent yield increase on Fe deficient soils | Improved chlorophyll and Fe tissue content            | Monreal <i>et al.</i> , 2016 <sup>[9]</sup>      |
| Iron oxide nanoparticles                        | Peanut ( <i>Arachis hypogaea</i> )     | Foliar spray              | Limited on Fe sufficient soils                       | No consistent NUE gain reported                       | Zulfiqar <i>et al.</i> , 2019 <sup>[19]</sup>    |
| Copper oxide nanoparticles                      | Tomato ( <i>Solanum lycopersicum</i> ) | Foliar spray              | Mixed, some yield suppression at higher dose         | Phytotoxic threshold close to agronomic dose          | Kah <i>et al.</i> , 2019 <sup>[6]</sup>          |
| Silica nanoparticles                            | Rice ( <i>Oryza sativa</i> )           | Soil application          | 5 to 10 percent yield increase                       | Improved silica deposition and lodging resistance     | Subramanian <i>et al.</i> , 2015 <sup>[15]</sup> |
| Nano hydroxyapatite (P carrier)                 | Soybean ( <i>Glycine max</i> )         | Soil application          | Comparable to conventional P at lower dose           | Reported P uptake efficiency gain of 20 to 30 percent | Liu and Lal, 2015 <sup>[8]</sup>                 |
| Nano urea (N carrier)                           | Wheat ( <i>Triticum aestivum</i> )     | Foliar spray              | Yield parity with reduced basal N                    | NUE gain contested, baseline dependent                | Kah <i>et al.</i> , 2018 <sup>[6]</sup>          |
| Nano urea (N carrier)                           | Rice ( <i>Oryza sativa</i> )           | Foliar spray              | Yield parity reported in several trials              | Field scale mass balance data still limited           | Raliya <i>et al.</i> , 2018 <sup>[12]</sup>      |
| Chitosan nanoparticle carriers (NPK)            | Maize ( <i>Zea mays</i> )              | Soil application          | 10 to 15 percent yield increase in pot trials        | Reduced leaching in column studies                    | Guo <i>et al.</i> , 2018 <sup>[5]</sup>          |
| Manganese oxide nanoparticles                   | Mung bean ( <i>Vigna radiata</i> )     | Foliar spray              | Small, inconsistent across sites                     | Micronutrient tissue content increased                | Preetha and Balakrishnan, 2017 <sup>[11]</sup>   |
| Titanium dioxide nanoparticles                  | Spinach ( <i>Spinacia oleracea</i> )   | Foliar spray              | No consistent yield benefit                          | Concerns over soil microbial community shift          | Kah <i>et al.</i> , 2019 <sup>[7]</sup>          |
| Silver nanoparticles (indirect nutrient effect) | Chickpea ( <i>Cicer arietinum</i> )    | Seed treatment            | Not primarily nutrient related                       | Included for toxicity comparison only                 | Kah <i>et al.</i> , 2018 <sup>[6]</sup>          |

### Controlled and Slow Release Fertilizer Technologies

Where nanofertilizers alter particle scale, controlled release fertilizers alter the barrier between the nutrient and the soil solution, typically through a polymer, sulphur, or biochar based coating applied to a conventional granule such as urea or diammonium phosphate. Shaviv (2001)<sup>[13]</sup> established much of the theoretical basis for describing release kinetics in these systems, characterising release as a function of coating thickness, water permeability and temperature, with most commercial products following either a sigmoidal or a near linear release curve over a period ranging from a few weeks to several months. The agronomic logic is straightforward, nitrogen is made available progressively across the crop growth cycle rather than being front-loaded at basal application, reducing the volatilization and leaching losses that occur when the full dose is applied as readily soluble urea.

The evidence for reduced nitrogen loss under controlled release regimes is comparatively strong relative to the nanofertilizer literature, in part because release kinetics can be measured directly in laboratory incubation studies before field deployment, giving researchers a mechanistic anchor that nanoparticle studies often lack. Azeem *et al.* (2014)<sup>[2]</sup> review a wide range of coating materials, including polyolefin, polyurethane, sulphur and various biodegradable polymers, and report that well-formulated coatings can extend nitrogen availability by several weeks while cutting cumulative ammonia volatilization by a third or more relative to uncoated urea. Naz and Sulaiman (2016)<sup>[10]</sup> reach broadly similar conclusions but raise a methodological caveat that recurs across this literature, namely that release kinetics measured in static water immersion tests do not map cleanly onto release under fluctuating field moisture and temperature, so that a coating validated in the laboratory may behave quite differently once deployed.

Cost remains the most consistently cited barrier to adoption, and it is here that controlled release fertilizers diverge sharply from

the nanofertilizer narrative of research promise outpacing commercial readiness. The coating process itself, rather than any component nutrient, drives the price premium, commonly cited at somewhere between thirty and eighty percent above conventional fertilizer depending on coating material and thickness (Trenkel, 2010)<sup>[17]</sup>. For smallholder cereal systems across much of South Asia, where per hectare fertilizer expenditure is already a binding constraint on adoption of any yield-enhancing input, this premium has confined controlled release products largely to high value horticultural and plantation crops, turf management and nursery production, rather than to the staple cereal systems where nitrogen loss is agronomically most consequential at a national scale. Solanki *et al.* (2015)<sup>[14]</sup> argue that biodegradable and locally sourced coating materials, including modified starches and biochar derived from crop residue, offer a route to narrowing this cost gap, though the release kinetics achievable with such materials remain less precisely characterised than those of the synthetic polymers that dominate current commercial formulations.

A further point of tension in this literature concerns synchrony between release rate and crop demand. A coating engineered to release nitrogen at a constant rate over ninety days does not necessarily match the nitrogen uptake curve of a rice or wheat crop, which is markedly non-linear, rising sharply during tillering and stem elongation and tapering during grain fill. Where release and demand curves diverge, controlled release fertilizers can under-supply nitrogen during peak demand while continuing to release it, at agronomically modest but environmentally relevant rates, well after the crop has stopped taking it up, undermining part of the environmental rationale for adopting the technology in the first place. Few of the trials reviewed here report uptake curves alongside release curves in a form that allows this synchrony to be assessed directly, which is itself a methodological gap worth flagging rather than a settled point of agreement or disagreement in the literature.

**Table 2:** Coating materials used in controlled release nitrogen fertilizers and their reported release characteristics

| Coating material                    | Typical release duration | Reported nitrogen loss reduction                          | Cost premium over urea | Reference                                    |
|-------------------------------------|--------------------------|-----------------------------------------------------------|------------------------|----------------------------------------------|
| Sulphur coating                     | 4 to 8 weeks             | 20 to 30 percent lower ammonia volatilization             | 30 to 40 percent       | Trenkel, 2010 <sup>[17]</sup>                |
| Polyolefin resin coating            | 8 to 16 weeks            | 35 to 45 percent lower leaching loss                      | 60 to 80 percent       | Azeem <i>et al.</i> , 2014 <sup>[2]</sup>    |
| Polyurethane coating                | 10 to 20 weeks           | Consistent, near linear release                           | 60 to 80 percent       | Azeem <i>et al.</i> , 2014 <sup>[2]</sup>    |
| Polyurethane sulphur hybrid coating | 6 to 12 weeks            | Intermediate performance between the two base materials   | 50 to 60 percent       | Naz and Sulaiman, 2016 <sup>[10]</sup>       |
| Biodegradable starch based coating  | 4 to 10 weeks, variable  | Field performance less consistent than synthetic polymers | 20 to 35 percent       | Solanki <i>et al.</i> , 2015 <sup>[14]</sup> |
| Biochar based coating               | 6 to 12 weeks            | Additional soil carbon co-benefit reported                | 15 to 25 percent       | Solanki <i>et al.</i> , 2015 <sup>[14]</sup> |
| Wax coating                         | 2 to 6 weeks             | Modest, shorter duration than polymer coatings            | 10 to 20 percent       | Shaviv, 2001 <sup>[13]</sup>                 |
| Lignin based coating                | 4 to 8 weeks             | Comparable to starch based coatings                       | 20 to 30 percent       | Naz and Sulaiman, 2016 <sup>[10]</sup>       |
| Zeolite matrix incorporation        | 6 to 14 weeks            | Improved cation exchange retention of ammonium            | 25 to 35 percent       | Trenkel, 2010 <sup>[17]</sup>                |
| Clay mineral coating (bentonite)    | 4 to 10 weeks            | Moderate reduction in leaching                            | 15 to 25 percent       | Azeem <i>et al.</i> , 2014 <sup>[2]</sup>    |

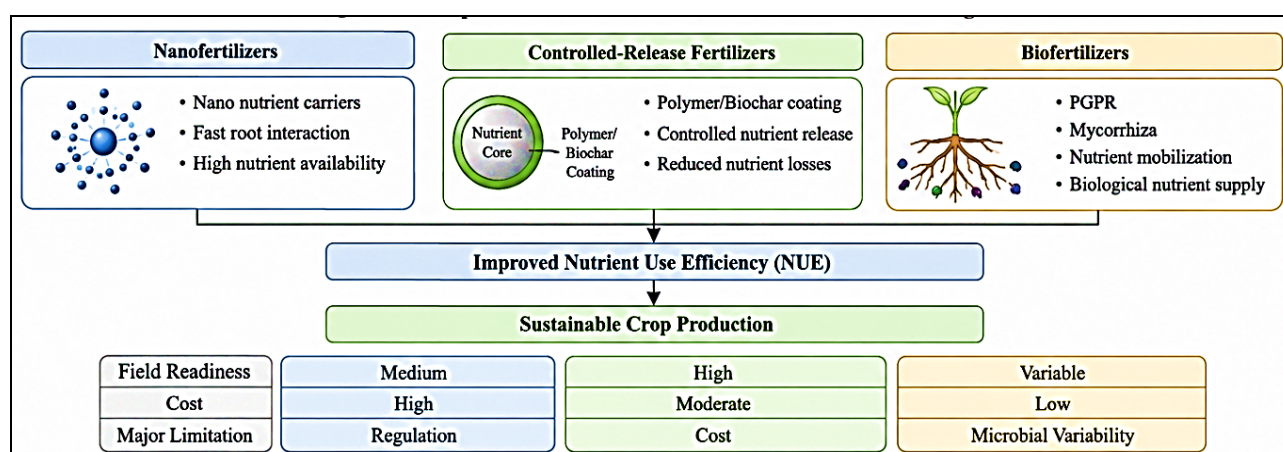
### Biofertilizers and Microbial Consortia as a Biologically Grounded Alternative:

Biofertilizers occupy a different conceptual space from the two preceding technologies because they do not deliver nutrients directly so much as mobilise, fix or solubilise nutrients already present, or otherwise inaccessible, in the soil. Plant growth promoting rhizobacteria, arbuscular mycorrhizal fungi and free-living or symbiotic nitrogen fixers such as *Azotobacter*, *Azospirillum* and *Rhizobium* species have each been developed as commercial inoculants, and their proposed mode of action ranges from direct nitrogen fixation to phosphate solubilisation through organic acid exudation, to indirect growth promotion via phytohormone production and induced systemic resistance (Vejan *et al.*, 2016)<sup>[18]</sup>. Adesemoye and Kloepper (2009)<sup>[1]</sup> frame this diversity of mechanism as both the strength and the central limitation of the approach, since a consortium selected for phosphate solubilisation in one soil type may contribute little where native phosphate fixing capacity is already saturated or where competing soil microbiota outcompete the introduced strain.

The comparative evidence on biofertilizer efficacy is considerably more heterogeneous than that reported for controlled release coatings, and arguably more heterogeneous than even the nanofertilizer literature, because biofertilizer performance depends on an ecological interaction between an introduced organism and a resident soil community that is itself variable across sites, seasons and tillage histories. Timmusk *et*

*al.* (2017)<sup>[16]</sup> survey field trial outcomes across cereal systems and report yield responses ranging from negligible to substantial for ostensibly similar inoculant formulations, attributing much of the variance to inoculant survival after application rather than to any inherent difference in the biological mechanism being exploited. This raises a question that the nanofertilizer and controlled release literatures do not have to confront in the same way, namely whether the product being tested in a trial is even the product that reaches the rhizosphere in viable form, since inoculant viability can decline sharply during storage, seed coating and soil application before the intended mechanism has any opportunity to operate.

Where biofertilizers converge with the smart fertilizer framing used elsewhere in this review is in formulations that combine microbial inoculants with polymer or biochar carriers designed to protect the organism during storage and improve survival after field application, effectively borrowing the controlled release logic to solve a viability problem rather than a nutrient release problem. This convergence is conceptually appealing but empirically underexplored, most comparative trials still test biofertilizers against synthetic fertilizers rather than testing carrier-protected biofertilizer formulations against unprotected ones, leaving open the more agronomically useful question of how much of the reported inconsistency in biofertilizer performance is attributable to formulation rather than to the underlying biological mechanism.

**Fig 2:** Comparative Framework of Smart Fertilizer Technologies

### Comparative Efficiency, Conflicting Evidence and Methodological Gaps

Placed side by side, the three technology streams reviewed here do not compete on equal evidentiary footing, and treating them as interchangeable options in a single smart fertilizer category obscures more than it clarifies. Controlled release fertilizers rest on the most mechanistically tractable evidence base, since release kinetics can be measured directly and reproducibly before any agronomic trial begins. Nanofertilizer evidence is comparatively promising but concentrated in pot and greenhouse conditions, with the field-scale mass balance studies needed to confirm genuine nutrient use efficiency gains, rather than mere reductions in applied rate, still relatively scarce (Kah *et al.*, 2018; Raliya *et al.*, 2018) <sup>[5, 12]</sup>. Biofertilizer evidence is the most internally inconsistent of the three, not because the underlying biological mechanisms are implausible but because inoculant viability and soil microbial context introduce a degree of trial to trial variability that neither of the other technologies has to contend with to the same extent (Timmusk *et al.*, 2017) <sup>[16]</sup>.

A recurring methodological weakness across all three literatures is the comparison baseline chosen for efficiency claims. Many trials compare a smart fertilizer applied at a reduced rate against a conventional fertilizer applied at the recommended full rate, which conflates two separate questions, whether the smart formulation delivers more nutrient per unit applied and whether the recommended full rate itself was agronomically appropriate for the trial site in the first place. Where trials do include an agronomically matched comparison, meaning conventional fertilizer applied at a rate calibrated to the same soil test values as the smart fertilizer treatment, reported efficiency gains for nanofertilizers in particular tend to narrow considerably relative to the headline figures cited in review articles (Guo *et al.*, 2018) <sup>[5]</sup>. This does not mean the underlying mechanisms are unreal, but it does mean that comparative efficiency claims drawn from the current literature should be read with some scepticism until the comparison baselines are standardised across trials.

A second gap concerns crop and soil generalisability. The bulk of nanofertilizer and biofertilizer trials cluster around a small number of crops, principally rice, wheat, maize and a handful of vegetable species, and around soils already known to be responsive to the specific nutrient being tested. Extrapolating reported efficiency gains to soils with different texture, pH or organic carbon status, or to crops with markedly different rooting architecture, remains a leap that the current evidence base does not fully support. Zulfiqar *et al.* (2019) <sup>[19]</sup> make a similar point in relation to nanofertilizers specifically, cautioning that particle behaviour in soil, including aggregation, adsorption to clay minerals and interaction with soil organic matter, is highly soil specific and cannot be assumed constant across the range of conditions under which farmers would actually deploy these products.

### Environmental, Regulatory and Economic Constraints on Adoption

Beyond the agronomic efficiency question sits a separate, and in practical terms more decisive, set of constraints on whether smart fertilizers move from research trial to field adoption. Regulatory frameworks for nanomaterial fertilizers remain underdeveloped in most jurisdictions, including India, where no dedicated nanofertilizer registration pathway existed at the time most of the literature synthesised here was published, leaving commercial release to proceed, where it happens at all, under conventional fertilizer or biostimulant registration categories not designed with nanoscale materials in mind (Preetha and

Balakrishnan, 2017; Chhipa, 2017) <sup>[11, 3]</sup>. This regulatory gap is not a minor administrative detail, it directly shapes which formulations reach farmers and which remain confined to research publication.

Environmental fate is the second major constraint, and here the evidence is genuinely mixed rather than simply thin. Some nanoparticle formulations show limited soil mobility and low off-site transport risk under typical agricultural moisture regimes, while others, particularly those based on more soluble or more reactive metal oxides, raise legitimate concern about accumulation in soil microbial communities and potential transfer through the food chain at concentrations that remain poorly characterised for chronic, repeated field application rather than single-season trials (Kah *et al.*, 2019) <sup>[6]</sup>. Controlled release fertilizers carry a related but distinct concern, since many commercial coatings rely on non-biodegradable polymers that persist in soil as microplastic residue once the nutrient core has been released, a trade-off that is rarely weighed against the nitrogen loss reductions the same coatings achieve.

Economically, the smallholder cost barrier already noted for controlled release fertilizers applies with comparable or greater force to nanofertilizers, whose production costs remain dominated by synthesis and stabilisation processes that have not yet achieved the economies of scale enjoyed by conventional granular fertilizer manufacture. Biofertilizers are the least expensive of the three streams to produce and distribute, which is part of why they remain the technology most actively promoted through public extension systems in India, yet the same cost advantage does not resolve the viability and shelf-life problems that undermine consistent field performance. Taken together, these constraints suggest that the pace of adoption for smart fertilizers will likely be governed less by further gains in laboratory efficacy and more by whether coating materials, nanoparticle synthesis routes and inoculant carrier systems can be redesigned around cost and regulatory feasibility from the outset, rather than treated as problems to be solved after the underlying mechanism has already been optimised.

### Conclusion

Smart fertilizers, taken as a category, promise a narrower gap between nutrient applied and nutrient absorbed than conventional granular fertilizer can achieve, and the mechanistic case for each of the three streams considered here, nanoscale carriers, controlled release coatings and microbial consortia, is individually sound. What this review has tried to show is that the category obscures real differences in evidentiary maturity between those streams, and that comparative efficiency claims made across the current literature rest on inconsistent baselines that have not yet been standardised. Controlled release fertilizers are the most field ready of the three, constrained principally by cost and by the biodegradability of coating materials rather than by any unresolved question about mechanism. Nanofertilizers carry the strongest laboratory rationale but the thinnest field validation, and the field trials needed to confirm genuine nutrient use efficiency gains, as distinct from reductions in applied rate, remain a priority for the coming years. Biofertilizers sit closest to the practical needs of smallholder systems on cost grounds alone, yet their inconsistent field performance will not be resolved by further strain selection so much as by solving the viability and carrier problems that determine whether an inoculant survives long enough to exert the mechanism it was selected for. Future research would be better served by trials designed around shared, agronomically matched comparison baselines and by carrier systems

engineered jointly for nutrient release and organism survival, rather than by the continued proliferation of single-site, single-season efficacy claims that this review has found difficult to reconcile with one another.

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