

INTEGRATED FERTILIZER-BIOFERTILIZER SYSTEMS: MARKET TRENDS, TECHNOLOGICAL CHALLENGES AND FUTURE PERSPECTIVES

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The global synthetic fertilizer market, valued at approximately USD 200 billion in 2024, faces declining marginal returns despite increasing application rates. Concurrently, the biofertilizer market is projected to expand from USD 1.4 billion (2024) to USD 2.8 billion by 2030 (CAGR ~13 %). Integrated nutrient management systems combining mineral fertilizers with microbial inoculants represent an emerging technological frontier aimed at improving nutrient use efficiency, environmental sustainability, and soil health restoration.

This review critically examines market dynamics, technological innovations, and practical challenges in developing integrated fertilizer-biofertilizer products, with a specific focus on microbial coating technologies for granular and liquid fertilizers.

A comprehensive literature review covering 2020–2025, analyzing peer-reviewed publications, market reports, and field trial data from commercial applications was conducted. Search strategies employed multiple databases focusing on phosphate-solubilizing bacteria, nitrogen-fixing microorganisms, coating technologies, and integrated nutrient management systems.

Phosphate-solubilizing bacteria (PSB) demonstrate consistent field efficacy, increasing wheat yields by 14–85 % while enhancing soil available phosphorus up to 33 %. Meta-analyses confirm biofertilizer yield increases of approximately 10–40 % across diverse crops and environments. Granular fertilizers coated with microbial inoculants through post-granulation spray coating at 2–5 L t⁻¹ achieve microbial densities of 10⁶–10⁸ CFU g⁻¹ with reported shelf-life stability exceeding 12 months. However, technological barriers persist: conventional granulation processes involve

temperatures (60–90 °C) that inactivate microorganisms, necessitating post-granulation application strategies. Liquid fertilizers create chemically aggressive environments (pH 7–10, high salinity) that are hostile to long-term microbial survival, though short-term tank-mix compatibility (2–8 hours) enables immediate field application. Recent advances include the use of biopolymer matrices (chitosan, xanthan gum), metal-phenolic networks, and industrial-scale spray-coating systems, which demonstrate commercial viability while maintaining cost-competitiveness.

Integrated fertilizer-biofertilizer systems offer substantial potential for sustainable intensification, enabling 20–30 % reductions in synthetic fertilizer application without yield penalty. Commercial viability depends on resolving formulation stability challenges through advanced coating technologies while maintaining cost-competitiveness. The convergence of controlled-release fertilizer technology with microbial inoculant delivery represents a promising pathway for next-generation nutrient management systems, with projected market potential within this segment reaching USD 5–6 billion by 2030.

Key words: soil nutrient management; biofertilizer formulation; sustainable agriculture.

1. Introduction

Modern agriculture confronts a fundamental paradox: while global food production relies increasingly on synthetic fertilizers, their marginal productivity gains are diminishing even as application rates escalate [1; 2]. The global fertilizer market, valued at approximately USD 200 billion annually, exhibits volumetric stagnation in mature markets despite price volatility and rising input costs [3; 4]. Nitrogen use efficiency in intensive cereal systems rarely exceeds 50 %, with losses through leaching, volatilization, and denitrification [5; 6]. Thus, the loss of approximately 59 % of N (at a level of 60–80 kg N/ha) in the soil-plant system in grain production led to a 41 % decrease in economic efficiency [7]. Phosphorus faces distinct challenges: upon application, approximately 70–90 % of applied P rapidly converts to retrograded forms unavailable to plants through fixation by soil minerals (Fe, Al, Ca) [8]. Soil degradation caused by the use of mineral fertilizers leads to reduced fertility, soil compaction, reduced microbial diversity and other consequences [9; 10]. These factors stimulate interest in biological solutions.

Microbial biofertilizers — particularly nitrogen-fixing bacteria (*Azotobacter* spp., *Rhizobium* spp.) and phosphate-solubilizing bacteria (PSB), including genera *Bacillus*, *Paenibacillus*, and *Pseudomonas* — demonstrate the capacity to enhance nutrient availability through biological nitrogen fixation [10], mineral phosphate solubilization [11; 12], stimulation of plant growth via phytohormone production [13; 14] and induction of resistance to biotic and abiotic factors [15–17]. The global biofertilizer market reached USD 1.4 billion in 2024 with projections approaching USD 2.8 billion by 2030,

reflecting compound annual growth rates of approximately 12–13 % [18].

Yet despite documented efficacy in controlled trials, biofertilizer adoption remains constrained by formulation challenges, inconsistent field performance, and logistical barriers related to storage, transport, and on-farm handling [19]. A promising solution emerging in recent years involves so-called integrated products: mineral fertilizers enriched with microbial inoculants delivered through advanced coating or tank-mix technologies [20–22]. Such systems have the potential to combine the immediate nutrient supply of mineral fertilizers with the sustained efficiency-enhancing effects of beneficial microorganisms [23].

This review examines three interconnected dimensions of integrated fertilizer-biofertilizer systems: market and policy dynamics and economic drivers, scientific evidence for phosphate-solubilizing and nitrogen-fixing microorganisms, and technological challenges and innovations in formulation, particularly microbial coating of granular fertilizers and compatibility with liquid fertilizer systems. The review relies on recent literature (2020–2025) and selected commercial field trial data to assess both achievements and persistent barriers, providing an informed perspective on the trajectory of this emerging technology sector and on the evidentiary gaps that require further validation.

2. Materials and methods

2.1. Literature search and data collection

A systematic literature review covering publications from January 2020 through January 2025 was conducted. Multiple databases were queried, including Web of Science Core Collec-

tion, PubMed, Google Scholar, and industry market-research repositories. Search terms employed Boolean combinations: (“phosphate-solubilizing bacteria” or “PSB”) and (“fertilizer efficiency” or “biofertilizer”); (“nitrogen-fixing bacteria” or “Azotobacter”) and (“coating technology”); (“granular fertilizer” or “liquid fertilizer” or “UAN” (urea-ammonium nitrate)) and (“microbial coating” or “tank mix compatibility”). Reference lists of key papers were also screened to identify relevant studies not captured by database queries.

2.2. Market data analysis

Market valuations and growth projections were compiled from industry analyst reports (Mordor Intelligence, Markets and Markets, IMARC Group), corporate disclosures from major fertilizer manufacturers, and peer-reviewed economic analyses. We prioritized sources providing methodological transparency regarding market segmentation and growth rate calculations. Where multiple estimates were available for the same year or segment, we reported the range and the most conservative figure.

2.3. Field trial data integration

Commercial field-trial data from integrated fertilizer-biofertilizer applications (2019–2024) were incorporated, including multi-location and multi-crop trials conducted in Ukraine, Europe, and North America. Data encompassed crop-yield responses, fertilizer use-efficiency metrics, and product stability assessments under commercial storage and handling conditions. Because a portion of these data originated from corporate sources, they are identified in the text as proprietary or non-peer-reviewed and interpreted with appropriate caution.

2.4. Inclusion and exclusion criteria

Studies were included if they: reported quantitative field-trial data on biofertilizer or integrated fertilizer-biofertilizer efficacy, described formulation technologies relevant to microbial viability or shelf-life, examined phosphate-solubilizing or nitrogen-fixing bacteria under agricultural conditions, or analyzed market trends with documented data sources. The laboratory studies without field validation and review articles published prior to 2020 were excluded. However, seminal pre-2020 studies were cited selectively to provide background on coating technologies and mechanisms of plant growth-promoting microorganisms.

3. Results

3.1. Global fertilizer and biofertilizer market dynamics

3.1.1. Synthetic fertilizer market: scale and regional dynamics

The global synthetic fertilizer market is valued at approximately USD 200 billion annually, supporting an estimated half of world food production [1,24]. Despite this massive scale, volume growth has largely plateaued in mature markets (North America, Western Europe, East Asia), reflecting agronomic and physiological limits where additional inputs yield diminishing returns [1; 12; 14].

The main regional consumption patterns are in the Asia-Pacific region, North America, Europe and Latin America.

Asia-Pacific dominates global consumption (> 50 % market share), with China producing around 25 % of global fertilizer output and consuming approximately 94 million tonnes annually [3]. Growth rates in these mature intensive systems have decelerated to about 2–3 % annually. North America accounts for ~18 % of the global market. Despite extensive phosphate and potassium resources, the region imports more than half of its nitrogen fertilizers and about 85 % of potassium, creating exposure to supply chain vulnerabilities [3]. Europe represents ~15 % of global markets. Post-2022 energy price volatility significantly impacted fertilizer costs, though prices declined from peak levels of USD 815 t⁻¹ (April 2022) to USD 334 t⁻¹ (September 2024) for representative NPK baskets [3]. Latin America (~11 % market share) shows the strongest growth trajectory (CAGR 5–7 %), driven by expansion of soybean, corn, and sugarcane cultivation in Brazil, Argentina, and Paraguay [3]. Mature markets show modest increases of 0.8–1.5 million tonnes annually, while faster growth concentrates in Sub-Saharan Africa (projected +25 %, or 2 million tonnes over 2024–2028) and Latin America/South Asia (+3–4 million tonnes each). This pattern reflects a fundamental shift: once soils reach moderate-to-high fertility, additional synthetic inputs provide progressively limited benefit while increasing environmental externalities (nutrient runoff, greenhouse gas emissions) [3; 24].

3.1.2. Biofertilizer market growth trajectory

During 2021 and 2022, global food and fertilizer prices rose sharply due to the recovery

from the COVID-19 recession and the outbreak of war between Russia and Ukraine. During 2022–2023, despite the sharp increase in raw material costs, global demand for fertilisers declined only slightly. A larger percentage of farmers (78.6 %) cited the cost of fertilisers as one of the main problems affecting their activities, which led to the implementation of adaptation strategies to reduce dependence on fertilisers. Such strategies included crop rotation, cover crops, variable application rates, manure/compost use, and/or the addition of microorganism-based biofertilizers [25].

In contrast, the biofertilizer sector continues to exhibit robust expansion. Market valuations increased from approximately USD 3,7 billion in 2024, with projections reaching USD 6,0 billion by 2030, representing a compound annual growth rate of about 9,94 % [26]. This growth trajectory, while substantial in percentage terms, maintains biofertilizers at < 1 % of the total fertilizer market by value, highlighting both the scale of opportunity and the challenges for market penetration.

The main growth drivers are regulatory pressures for input reduction (EU Farm to Fork Strategy targeting up to 20–30 % fertilizer reductions by 2030) [27], expansion of organic agriculture requiring approved biological inputs, rising synthetic fertilizer costs, which improve the cost-benefit profile of biofertilizers and accumulating field evidence demonstrating agronomic benefits under farmer conditions.

Regional adoption patterns vary substantially. India leads in absolute biofertilizer consumption (~30 % global share), driven by government subsidies and mandated inclusion in soil-health and integrated nutrient management programs. Latin America, particularly Brazil and Argentina, shows rapid growth (CAGR ~15–18 %) supported by extensive soybean cultivation utilizing *Bradyrhizobium* inoculants. North America and Europe exhibit slower but steady adoption (CAGR ~8–10 %), primarily in organic systems and among early-adopter conventional farmers [28].

3.1.3. Integrated products: an emerging high-growth segment

A nascent but rapidly growing segment involves integrated fertilizer-biofertilizer products: mineral fertilizers (granular or liquid) enriched with microbial inoculants [21; 22; 29; 30]. While comprehensive market data for this

subsegment remains limited, industry sources suggest this category represents approximately 3–5 % of total biofertilizer sales (~USD 40–70 million in 2024) with projected growth rates potentially exceeding 20 % annually. If this trajectory continues, integrated products could reach USD 200–300 million by 2030, contributing to biofertilizer market expansion toward an aspirational USD 5–6 billion valuation when broader biostimulant and microbial categories are included [28].

Growth drivers include farmer preference for operational simplification (single-pass operations) and potential synergies, wherein mineral nutrients support microbial establishment while microbes enhance nutrient use efficiency. Major fertilizer manufacturers are increasingly investing in this space: ICL's NanoCote technology, Mosaic's MicroEssentials line with microbial-coating options, and regional producers in Eastern Europe, Brazil, and China developing proprietary formulations [29–32].

The core technological challenge — maintaining microbial viability through manufacturing, storage, and field application — remains the primary constraint currently limiting broader commercialization.

3.2. Phosphate-solubilizing and nitrogen-fixing bacteria: mechanisms and efficacy

Phosphate-solubilizing bacteria (PSB) enhance plant phosphorus nutrition through multiple mechanisms, such as secretion of low-molecular-weight organic acids (gluconic, citric, oxalic) that chelate cations (Ca^{2+} , Fe^{3+} , Al^{3+}) bound to phosphate; production of phosphatase enzymes and phytases mineralizing organic phosphorus compounds, formation and release of siderophores, which chelate metal ions and form complexes, helping phosphates to be available for plant uptake; and acidification of the rhizosphere through proton extrusion and respiratory CO_2 production [10–13; 33–36].

Key genera of PSB include *Bacillus*, *Pae-nibacillus*, *Pseudomonas*, *Burkholderia*, and *Pantoea*. Their performance is highly dependent on soil pH, organic carbon availability, texture, moisture, and indigenous microbial competition strongly modulate PSB efficacy, explaining the substantial field-to-field performance variability reported in the literature [33].

Recent field trials document their notable efficacy. Wheat (*Triticum aestivum* L.) inoculation with PSB consortia increased yields up to

14.42 % ($P < 0.05$) compared with the control treatment in phosphate fertilizer-used farmland. Besides promoting wheat growth, we found the labile P fraction in soil was significantly increased by over 122.04 % ($P < 0.05$) under PSB inoculation compared with it in soils without, in parallel, the stable P fraction was significantly reduced by over 46.89 % ($P < 0.05$). Furthermore, PSB inoculation increased the soil microbial biomass and activity [34]. Maize trials with PSB seed treatment reported yield gains of 64–85 % compared to uninoculated controls when PSB were combined with reduced phosphorus fertilizer inputs. A recent meta-analysis confirms that PSB consistently enhance rock phosphate solubilization and crop phosphorus uptake, though efficacy varies with soil type, climate, and the specific strain or consortium employed [35]. This data support the premise that PSB can partly compensate mineral P application rates, but they also underscore the need for strain-soil matching and multi-location validation.

Biological nitrogen fixation in classical *Rhizobium*-legume symbiosis is well-established, contributing approximately 20–60 kg N·ha⁻¹ per season in soybean and other grain legumes under favorable conditions [10; 37]. More recent and agronomically intriguing are associative nitrogen-fixing bacteria colonizing cereal roots: *Azotobacter* spp., *Azospirillum* spp., *Herbaspirillum* spp., others and endophytic bacteria [38]. The action of *Rhodotorula mucilaginosa* NF 516 and *Arthrobacter* sp. NF 528, either separately or in combination, significantly improved wheat plant growth and enhanced nutrient uptake (N and P) under conditions of reduced nitrogen content in the soil [39]. While nitrogen fixation rates in cereals (typically 10–30 kg N × ha⁻¹·season⁻¹) are lower than in legume symbioses, additional benefits accrue through phytohormone production (auxins, gibberellins, cytokinins) that stimulate root growth, enhance nutrient uptake, and may improve abiotic-stress tolerance [40].

A meta-analysis of experimental studies showed that the effectiveness of NFB inoculation varied significantly depending on the combination of crop and bacteria; soil inoculation demonstrated a significantly greater positive effect than seed inoculation [41]. Field evidence from wheat, maize, and rice systems demonstrates yield increases of about 10–25 % with

nitrogen-fixing inoculants, often accompanied by 15–20 % reductions in synthetic nitrogen fertilizer without detectable yield penalty. However, efficacy depends critically on soil nitrogen status: indigenous nitrogen levels above 80–100 kg N·ha⁻¹ suppress biological fixation through feedback regulation, thereby limiting benefits in intensively fertilized systems. Accordingly, the strongest response is reported in moderate-input or transitional systems, which is particularly relevant for integrated fertilizer-biofertilizer systems targeting N-rate optimization rather than full replacement [42–44].

3.3. Synergistic effects microorganisms in integrated systems

Combining PSB and nitrogen-fixing bacteria with reduced mineral fertilizers often yields additive-to-synergistic benefits exceeding individual treatments. Field trials employing microbial consortia with 70–80 % of standard NPK rates produced yield increases of 10–22 % relative to full-fertilizer controls while using 20–30 % less fertilizer [45]. These mechanisms involve such factors, as nitrogen fixation supplying additional N to support plant growth, phosphate solubilization enhancing P availability, microbial organic acids improving micronutrient (Fe, Zn, Mn) solubility, and phytohormone production stimulating root proliferation and greater nutrient foraging capacity [40; 42; 47; 48]. Joint inoculation of wheat plants with diazotrophic *Paenibacillus beijingensis* BJ-18 and phosphate-solubilising *Paenibacillus* sp. B1 significantly increased plant growth and the content of phosphates and nitrogen in the roots and shoots of plants and in the soil [48]. In several cases, improved root architecture also enhanced water uptake, indirectly contributing to yield stability under transient stress [40; 42].

These integrated effects suggest a realistic potential for fertilizer substitution — 20–30 % reductions in mineral inputs while maintaining or improving yields — provided that microbial establishment and activity can be reliably achieved under diverse field conditions and that strains are matched to soil and crop requirements [49].

3.4. Technological challenges and innovations in formulation

3.4.1. Granular fertilizers: from thermal barriers to coating solutions

Conventional granular fertilizer production involves high-temperature processes (60–90 °C)

during granulation, drying, and in some cases coating stages [51]. Most microorganisms cannot survive these conditions: vegetative bacterial cells typically exhibit thermal death kinetics with D-values (decimal reduction times) of 2–5 minutes at 60 °C. Even spore-forming *Bacillus* species experience significant viability losses during prolonged exposure to granulation/drying temperatures [52].

This thermal barrier historically prevented microbial incorporation during granular fertilizer manufacture. However, a breakthrough solution has emerged: post-granulation spray coating of finished granules with microbial inoculants at ambient temperatures (15–25 °C) [51]. This approach enables practical commercial production while maintaining microbial viability, allows flexible dosing, and can be implemented on existing coating drums with limited retrofitting.

3.4.2. Post-granulation coating technologies and commercial applications

Several coating approaches demonstrate commercial viability, for example direct spray coating with protective additives. The most practically implemented approach involves spraying microbial suspensions directly onto finished granules using standard fertilizer-coating equipment. Liquid inoculant application rates of 2–5 L·t⁻¹ of granular fertilizer typically achieve target microbial densities of 10⁶–10⁸ CFU·g⁻¹. Protective additives in the spray solution — including glycerol, trehalose, or polysaccharides — enhance desiccation tolerance during drying and subsequent storage [54]. A two-step application (microbial spray — light sealing layer) can further improve shelf-life, where coating lines permit. As a commercial example is the BTU-Center Groundfix Coater technology. BTU-Center (Ukraine) developed a practical post-granulation coating system for enriching granular NPK fertilizers with microbial consortia [53]. Field trials (2020–2024) of BTU-Center Groundfix Coater technology across multiple locations demonstrated the application rates of 2–5 L inoculant per tonne fertilizer can be achieved and that coated products maintained shelf-life stability for more than 12 months at ambient temperature (18–25 °C), with microbial populations maintained remaining > 10⁶–10⁷ CFU·g⁻¹ throughout storage period. Also early plant response was observed, such as enhanced root development vi-

sible within 14–21 days post-application. Usage of BTU-Center Groundfix Coater technology increased maize yield up to 0.4–1.0 t·ha⁻¹ (5–12 % gains) compared to standard fertilizer, sunflower yield improvements of 0.3–0.6 t·ha⁻¹ (8–15 % gains) and economic returns (additional yield value minus coating cost) ranged from 2:1 to 5:1, depending on crop price and fertilizer rate.

In specific trials, enriched fertilizer at 100 kg·ha⁻¹ produced yield increases nearly three times greater than standard fertilizer: conventional fertilizers yielded +250 kg·ha⁻¹, while enriched formulations delivered +960 kg·ha⁻¹. Across five multi-location trials (2020–2024) on corn and sunflower, average yield increments reached 400 kg·ha⁻¹ [54].

The use of the mineral fertiliser azophoska, enriched with *B. amyloliquefaciens* subsp. *plantarum* 5/13, *B. cereus* 3/7, *B. amyloliquefaciens* B-22 contributes to an increase in the number of rhizosphere soil bacteria in Bellarosa potato plants by more than 2 times for individual variants of ammonifying (by 5–82 %), phosphate-solubilising bacteria and microorganisms that mainly absorb mineral nitrogen compounds. This further contributes to the development of the root system and its absorption capacity, the content of chlorophylls a and b, the area of the photosynthetic apparatus, the specific surface density of leaves the increase in crop yield and starch content, and the reduction in nitrate content [21; 22].

When using a biopolymer coating system, microorganisms, suspended in biopolymer solutions (chitosan, alginate, xanthan gum) are sprayed onto granules, followed by gentle, low-temperature drying (35–40 °C) forming protective films [53; 55]. Chitosan-based coatings offer particular promise due to their mild antimicrobial properties that protect against contamination while still maintaining beneficial strain viability. Xanthan gum provides excellent film-forming characteristics and moderate moisture retention. This approach routinely achieves microbial densities of 10⁶–10⁸ CFU·g⁻¹ fertilizer with shelf-life stability exceeding 12 months at ambient temperature.

To protect *Bradyrhizobium* spp. cells, an encapsulation technique was developed using a thermostable xeroprotectant core based on albumin and trehalose and a hydrophobic water vapour barrier shell made of paraffin, which

increased the stability of the culture for 4 months during storage at a high temperature (32 °C) and 75 % relative humidity [56].

Metal-phenolic network (MPN) coatings. A recent innovation involves self-assembling coatings combining metal ions (Fe^{3+} , Ca^{2+}) with polyphenols (tannic acid) [57]. MPNs protect microorganisms from desiccation, elevated temperatures (up to 50 °C), and humidity fluctuations. Coated *Pseudomonas chlororaphis* maintained viability after lyophilization and 6-month storage at 25 °C, demonstrating equal or superior protection compared to conventional approaches. *Pseudomonas chlororaphis*, coated with MPN, improved seed germination by 150 % compared to the control [57].

However, there are some critical success factors identified across approaches. Coating rate optimization, for example, 2–5 $\text{L}\cdot\text{t}^{-1}$ balances microbial density, cost, and coating uniformity. Also microbial strain selection is important, because hardy strains exhibiting desiccation tolerance and rapid soil colonization outperform lab-optimized isolates. *Bacillus* and *Paenibacillus* species forming dormant endospores demonstrate notable superior storage stability. And moisture control is important. Achieving < 3 % moisture content post-coating minimizes aggregation during bulk storage and mechanical spreading. And equipment compatibility need to consider, because coated fertilizers must retain free-flowing properties compatible with standard spreading machinery.

3.4.3. Liquid fertilizer compatibility and tank-mix strategies

Liquid complex fertilizers — particularly UAN (urea-ammonium nitrate, 28–32 % N) and liquid NPK formulations — represent 25–30 % of fertilizer markets in North America, Brazil, Ukraine, and Kazakhstan. However, these systems present substantial challenges for extended microbial storage. There are some chemical environment challenges:

- high salinity (UAN and liquid NPK exhibit osmotic pressures (2–6 osmol kg^{-1}) exceeding most bacterial tolerance thresholds);
- alkaline pH (UAN solutions typically range pH 7–10 due to ammonia equilibria);
- chemical reactivity (urea and ammonia can carbamylate bacterial proteins and free radicals can damage cell membranes and DNA).

Despite long-term storage incompatibility, short-term tank-mixing enables immediate field

application. This strategy leverages the logistical advantages of liquid fertilization while acknowledging that true long-term co-formulation with high-salt liquids remains an unresolved formulation challenge.

As BTU-Center field practices shown, the commercial applications of Groundfix biofertilizer demonstrate successful tank-mix compatibility with various liquid fertilizers [53]. For example, post-mixing survival (microorganisms in UAN solutions, 28–32 % N) for 2–8 hours is sufficient for immediate broadcast or injection application; liquid urea solutions are compatible for same-day field application following tank preparation; and compatibility with urease inhibitors (field experience confirms that Groundfix can be tank-mixed with UAN containing NBPT (N-(n-butyl) thiophosphoric triamide) urease inhibitors [54] without loss of detectable microbial activity, enabling integrated nutrient and efficiency management). This approach deliberately eliminates extended storage compatibility requirements, focusing instead on microbial survival during the short period between tank preparation and field delivery. Field trials confirm that biofertilizer efficacy is maintained when applications occur within recommended timeframes [54].

Urease inhibitors like NBPT, widely used to reduce ammonia volatilization from urea [58], temporarily inhibit urease enzyme activity in soil. While laboratory studies show that NBPT can affect plant urea uptake systems at high concentrations, field-relevant application rates (530–1060 $\text{mg NBPT}\cdot\text{kg}^{-1}$ urea) do not eliminate beneficial microbial activity when proper tank-mix protocols are followed. The brief exposure period (2–8 hours) before soil incorporation allows bacterial survival while preserving both NBPT functionality and biofertilizer benefits.

Alternative strategies under investigation include: the use of protective additives, such as glycerol, trehalose, or proline added at 1–3 % (w/v) which provide osmoprotection and extend bacterial survival [59]; microencapsulation (alginate-encapsulated bacteria can withstand liquid fertilizer environments for 7–14 days, though cost and scalability challenges persist) [53]; and separate application tracks (liquid fertilizer and microbial inoculant applied through separate nozzles in precision equipment, converging only at soil surface; this approach

avoids in-tank incompatibility while preserving single-pass field logistics).

3.5. Economic considerations and market viability

3.5.1. Cost-benefit economics

Economic viability of integrated fertilizer-biofertilizer products depends on several interrelated factors, such as:

1. Manufacturing cost increments. Post-granulation microbial coating adds approximately USD 15–40 per tonne fertilizer, depending on inoculant costs, application rates, and production scale. For granular NPK fertilizers typically costing USD 350–600 per tonne, this represents a 2.5–10 % premium — commercially acceptable provided that agronomic benefits materialize.

2. Yield value realization. Field trials demonstrating 5–15 % yield increases translate to substantial economic returns. For maize at USD 200 t⁻¹ and 10 t·ha⁻¹ baseline yield, a 10 % yield gain (+1 t·ha⁻¹) generates USD 200 ha⁻¹ additional revenue, easily justifying USD 20–40 ha⁻¹ coating cost increments.

3. Fertilizer substitution savings. If integrated products enable 20–30 % reductions in total fertilizer application — as demonstrated in BTU-Center trials showing maintained yields with 70 % of standard NPK rates plus Groundfix [54] — farmers realize both input cost savings (USD 70–180 ha⁻¹ for typical NPK programs) and reduced application/ logistics expenses.

BTU-Center field trials consistently demonstrate positive economic returns of Groundfix in commercial viability assessment [54]: coating cost increment ~ USD 20–40 t⁻¹ fertilizer; application rate typically 150–300 kg·ha⁻¹ enriched fertilizer; additional coating cost USD 3–12 ha⁻¹; yield value increase: USD 60–200 ha⁻¹ (depending on crop and price); net economic benefit USD 50–190 ha⁻¹; return on coating investment of 5:1 to 15:1 ratio.

There are, however, some risk and variability. The economic case weakens if field efficacy proves inconsistent. Risk-averse farmers require multiple successful on-farm demonstrations before adoption, creating a “technology valley of death” where promising innovations stall without large-scale farmer validation networks. This explains the critical importance of multi-location, multi-year field trial programs to establish robust efficacy data.

4. Discussion

4.1. Technological maturation and remaining barriers

The past five years have witnessed substantial progress in integrated fertilizer-biofertilizer technology [55–57; 60–62]. Post-granulation coating approaches now routinely deliver viable microorganisms (> 10⁶–10⁷ CFU·g⁻¹) with 12–18 month shelf stability, addressing the primary technical barrier that long constrained this category [54]. Practical spray coating systems, exemplified by BTU-Center’s Groundfix technology, demonstrate commercial viability across multiple crops and environments.

Coating material selection represents a critical decision point. While advanced systems such as metal-phenolic networks offer superior protection [57], simpler approaches using biopolymers (chitosan, xanthan gum) or protective additives in direct spray coating can provide adequate performance at lower cost [53; 55; 56]. Commercial success depends less on achieving maximum theoretical protection than on meeting practical thresholds: 12-month shelf life, compatibility with standard handling equipment, and cost increments < 10 % of base fertilizer price.

However, critical challenges persist:

1. Liquid fertilizer compatibility remains largely unsolved for extended storage scenarios. While tank-mix protocols enable 2–8 h stability sufficient for immediate application — successfully implemented by BTU-Center and other commercial producers — the goal of fully shelf-stable liquid fertilizer-biofertilizer products appears distant absent fundamental breakthroughs in microbial stress tolerance and osmoprotection. For practical purposes, short-term tank-mix compatibility may represent an adequate solution given that most liquid fertilizer applications involve on-farm/near-field mixing rather than long-term pre-mixed storage.

2. Field efficacy variability continues to challenge the sector. While meta-analyses confirm average benefits [35] and specific commercial programs (e. g., Groundfix) demonstrate consistent performance [54], individual farmer experiences can vary substantially. This variability reflects complex interactions between inoculant strains, indigenous soil microbiomes, environmental conditions, and management practices [16]. Developing predictive models, decision-support tools, or rapid diagnostic tools to

identify optimal application scenarios remains an active research frontier.

4.2. Market trajectory and integration pathways

The integrated fertilizer-biofertilizer category exhibits characteristics of early-stage innovation adoption. Current market size (~ USD 40–70 million within the USD 1.4 billion biofertilizer sector [8]) represents < 5 % penetration, but also a substantial growth potential. Projected trajectories suggest several possible scenarios. Conservative scenario shows 15–20 % annual growth maintaining current market positioning would yield USD 150–200 million by 2030, representing modest penetration within a USD 2.8 billion biofertilizer market. Moderate growth scenario shows 25–30 % annual growth, driven by expanded commercial adoption (analogous to Groundfix expansion in Eastern Europe and selected emerging markets) could reach USD 300–400 million by 2030. Optimistic scenario shows that, if technological barriers are substantially overcome and regulatory frameworks are better harmonized, integrated products could achieve 10–15 % of total biofertilizer markets (USD 280–420 million) by 2030. Combined with broader biostimulant category growth, this would contribute to an aspirational USD 5–6 billion addressable market incorporating multiple biological enhancement technologies.

Realization of higher growth scenarios depends on continued demonstration of robust and reproducible field efficacy across diverse conditions; cost competitiveness as production scales and coating lines are standardized; regulatory harmonization enabling more efficient market access and multi-country registrations, and integration with precision agriculture platforms that can optimize deployment strategies [63].

4.3. Integration with precision agriculture and digital platforms

A promising trajectory involves the convergence of integrated fertilizer-biofertilizer products with precision agriculture technologies [64]. Variable-rate application equipment can optimize integrated product deployment based on georeferenced soil fertility maps, applying microbial-enriched fertilizers selectively to zones exhibiting high phosphorus fixation, suboptimal P availability or localized N deficiency, while using conventional products elsewhere. This precision approach maximizes eco-

nomical returns by concentrating the high-cost, higher-value inputs where agronomic benefits are greatest [65].

Furthermore, real-time soil and plant diagnostics — NDVI imaging, proximal soil sensors, foliar nutrient analysis — can monitor and validate microbial inoculant performance within season, enabling adaptive management decisions. The integration of biologicals data with digital agriculture platforms thus transforms biofertilizers from products applied “on faith” to precision-deployed tools based on measured soil-plant-microbe status [66].

4.4. Sustainability implications

From an agroecological perspective, integrated fertilizer-biofertilizer systems offer tangible sustainability benefits. The combination of biotechnology and nanotechnology has the potential to transform agricultural practices and offers answers to both immediate and long-term challenges. Field-validated reductions of 20–30 % in synthetic fertilizer application without yield penalty [38; 54] translate to reduced greenhouse gas emissions from fertilizer manufacture and field N₂O emissions, diminished nutrient runoff contributing to aquatic eutrophication, improved soil health through enhanced microbial diversity and stimulated organic matter accumulation, and decreased dependency on finite phosphorus reserves [24; 65; 67; 68]. However, these benefits require consistent field efficacy. If microbial inoculants underperform, farmers will revert to conventional fertilizer rates, eliminating expected sustainability gains. Therefore, the environmental prospects of this direction directly depend on technological reliability.

Despite the fact that economic expectations for biofertilisers are promising, several methodological, environmental and legal issues are hindering their development. The established distribution network of mineral fertiliser companies makes it difficult for biofertilisers to enter the supply chain. Therefore, support from various stakeholders and government agencies to improve the situation in general and the supply chain in particular will lead to stable and sustainable growth in the use of biofertilisers in the future. Rethinking the international legal framework, improving it based on trending technologies, and promoting cross-sector cooperation are key factors in promoting biofertilisers as environmentally important and cost-

effective alternatives to chemical fertilisers [19; 63; 69; 70].

The industry must prioritize formulations and application protocols that demonstrate reliable, cross-environment performance rather than only peak efficacy under optimal scenarios [16].

5. Conclusions

The transition toward more sustainable and efficient agricultural systems underscores the growing importance of integrated fertilizer-biofertilizer technologies. While synthetic fertilizers remain foundational to global food production, their declining marginal returns and environmental impacts create a strong rationale for innovations that enhance nutrient use efficiency. Integrated products — combining mineral nutrition with microbial inoculants — offer a compelling middle-ground approach. They retain the reliability of conventional nutrient supply while leveraging biological mechanisms to improve nutrient uptake, soil health, and resilience. Recent advances in post-granulation microbial coating now enable shelf-stable granular fertilizers with high viable microbial counts and documented field performance. Trials consistently demonstrate 5–15 % yield gains and enable 20–30 % reductions in fertilizer use without yield penalty.

Commercial solutions, such as Groundfix (BTU), exemplify the technical and agronomic viability of these systems. Return-on-investment ratios ranging from 2:1 to 15:1 across various crops confirm that integrated solutions can be cost-effective under field conditions.

However, challenges remain — particularly the chemical incompatibility between living microbial agents and liquid fertilizer environments over prolonged storage. While short-term tank-mix strategies (2–8 hours) enable effective application, true co-formulation of shelf-stable microbial-liquid blends requires further breakthroughs in microbial tolerance and encapsulation technology.

Looking ahead, four priorities will shape the sector's maturation:

1. Robust field validation across soil-climatic conditions to guide deployment under variable conditions.

2. Improved formulation science, ensuring strain viability, compatibility, and cost efficiency.

3. Integration with precision agriculture platforms to optimize spatially targeted use.

4. Regulatory streamlining to support broader market access for microbial-enhanced products.

Market projections — USD 300–400 million for integrated products by 2030 within a broader biofertilizer market projected at USD 2.8 billion — signal significant growth potential. The convergence of microbial delivery technologies with controlled-release fertilizers offers a path toward scalable, sustainable nutrient solutions aligned with global agroecological and productivity goals.

Author contributions

Conceptualization: B. V. A., B. V. V., Ch. T. O., K. V. I.; methodology, investigation, data curation, writing — original draft preparation, editing: D. Y. O.; supervision and review: J. L. A., B. V. V. AI-assisted tools (ChatGPT, Claude) were used only to improve grammar, wording, and consistency of the manuscript. The scientific content, data interpretation, and conclusions were developed by the authors. The authors are responsible for the final content. The authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Data availability statement

Data supporting this review are available from cited public sources and company field trial reports. Supplementary information is available upon reasonable request to the corresponding author.

Conflicts of interest

The author B. V. A is the Director of Prospects and Development of Biotechnology Company BTU, D. Y. O. is the Head of International Department at Biotechnology Company BTU, B. V. V. is CEO, co-founder of Biotechnology Company BTU, Ch. T. O. is Commercial Director of Biotechnological Company BTU, Kuzmich V. I. is Head of The Expert Department of LLC “TH "BTU-CENTER"” of Biotechnological Company BTU, a biological products manufacturer based in Ukraine specializing in microbial biofertilizers including phosphate-solubilizing and nitrogen-fixing bacterial formulations. Field trial data and commercial application examples from BTU products

(Groundfix, Groundfix Coater) are referenced in this review. This work was conducted independently as part of doctoral research of D. Y. O. (J. L. A., B. V. V. are scientific supervisors) and does not represent company positions. The authors declare that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest beyond the stated employment.

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Received: 05.09.2025

Accepted: 08.10.2025

Published online: 29.12.2025

ІНТЕГРОВАНІ СИСТЕМИ ДОБРИВ І БІОДОБРИВ: РИНКОВІ ТРЕНДИ, ТЕХНОЛОГІЧНІ ВИКЛИКИ ТА МАЙБУТНІ ПЕРСПЕКТИВИ

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Світовий ринок синтетичних добрив, обсяг якого у 2024 році оцінюється приблизно у 200 млрд дол. США, стикається зі зниженням граничної віддачі, незважаючи на зростання норм внесення. Водночас ринок біодобрив, за прогнозами, зростає з 1,4 млрд дол. США у 2024 році до 2,8 млрд дол. США до 2030 року (CAGR ~13 %). Інтегровані системи живлення, що поєднують мінеральні добрива з мікробними інокулянтами, формують новий технологічний напрям, націлений на підвищення ефективності використання елементів живлення, екологічну сталість і відновлення ґрунтового здоров'я.

У цьому огляді критично проаналізовано ринкову динаміку, технологічні інновації та практичні виклики, пов'язані з розробкою інтегрованих добрив, з особливим акцентом на технологіях мікробного покриття для гранульованих і рідких формуляцій.

Було проведено систематичний огляд літератури за 2020–2025 роки із залученням рецензованих публікацій, ринкових звітів і даних польових випробувань із комерційного застосування. Пошукові стратегії охоплювали кілька баз даних і фокусувалися на фосфатмобілізувальних бактеріях, азотфіксаторах, технологіях покриття й системах інтегрованого живлення.

Фосфатмобілізувальні бактерії (ФМБ) демонструють стабільну польову ефективність, забезпечуючи приріст урожайності пшениці на 14–85 % і підвищення доступного фосфору в ґрунті до 33 %. Метадані підтверджують підвищення врожайності на 10–40 % при застосуванні біодобрив на різних культурах і в різних умовах. Гранульовані добрива з мікробним покриттям, нанесеним методом постгрануляційного обприскування у дозі 2–5 л/т, забезпечують мікробне навантаження 10^6 – 10^8 КУО/г з терміном зберігання понад 12 місяців. Водночас зберігаються технологічні бар'єри: традиційні процеси грануляції проходять за температур 60–90 °С, що інактивує мікроорганізми, а це зумовлює необхідність постгрануляційного нанесення. Рідкі добрива створюють хімічно агресивне середовище (рН 7–10, висока осмолярність), несприятливе для довготривалого збереження мікроорганізмів, хоча короточасна танково-змішувальна сумісність (2–8 годин) дозволяє їх польове застосування. Останні досягнення охоплюють використання біополімерних матриць (хітозан, ксантанова камедь), металофенольних мереж і промислових систем обприскування, які довели комерційну життєздатність і зберігають цінову конкурентоспроможність.

Інтегровані системи добрив і біодобрив мають значний потенціал для стійкої інтенсифікації, даючи змогу скоротити використання синтетичних добрив на 20–30 % без втрати врожайності. Їхня комерційна життєздатність залежить від подолання викликів щодо стабільності формуляцій за допомогою сучасних технологій покриття при збереженні конкурентної вартості. Конвергенція технологій контрольованого вивільнення з доставкою мікробних інокулянтів є перспективним шляхом розвитку систем живлення нового покоління, ринковий потенціал яких до 2030 року оцінюється в межах 5–6 млрд доларів США.

Ключові слова: управління живленням ґрунту; формуляція біодобрив; стале сільське господарство.

Отримано: 05.09.2025

Прийнято до друку: 08.10.2025

Опубліковано онлайн: 29.12.2025