Use of bio-inputs in large-scale agricultural systems

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2019 Nuffield Brazil Scholar

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Executive Summary

This report analyzes the use of bio-inputs – especially bio stimulants and microbial inputs – in large-scale agricultural systems in Brazil and abroad, seeking to separate solid evidence from promises still under testing. Based on technical review, international trips, and case studies on large farms, the central conclusion is that bio-inputs already have well-defined uses in some situations (such as inoculants for legumes, mycorrhizae in phosphorus-poor soils, and some biopesticides), but their delivery at scale depends heavily on context, management design, and governance.

The work describes three main trends. First, the consolidation of mature uses (inoculants for soybeans and sugarcane, biocontrol for certain targets, and certain special fertilizer programs designed based on-farm variability). Second, the expansion of practices such as additive composting, liquid biofertilizers, and microbial consortia, often linked to circular farm models and crop-livestock-forestry integration. Third, the growth of on-farm biological production is now supported by specific regulations and strong economic incentives but faces clear challenges in standardization, quality, and technical responsibility.

The cases visited in North America, Europe, Oceania, and Brazil converge on some patterns. Technologically, the most consistent results are achieved when bio-inputs are introduced as part of a package of practices (soil, plant, climate, logistics) rather than as a "magic product." Economically, the solutions that scale are those with moderate investment, clear ROI, and minimal need for additional machinery. In governance, successful cases have in common intentional decisions to innovate, test in pilot areas, measure rigorously, and scale up or down based on data, not a commercial narrative.

A critical point is the design of field tests. In large areas, small physical gains can be lost in the natural variability of the plot if there are no well-defined test strips, clear controls, and at least two evaluation seasons. Therefore, the report emphasizes that bio-inputs should be evaluated using broader metrics than bags/ha, including interannual stability, operating margin, basic soil indicators, and operational risk. Without this rigor, decisions oscillate between uncritical enthusiasm and premature rejection, wasting time and capital.

The conclusions organize the learnings into three layers: what is robust today (inoculants, some bio controls, targeted applications of bio stimulants, and well-designed special fertilizer programs), what is promising (applied soil microbiology, circular farms, well-structured on-farm systems), and what we still don't know (aggregate economic impact on hundreds of thousands of hectares, long-term effects on resilience, and regulatory and market limitations). The final message to large-scale producers is one of informed pragmatism: start with concrete problems, test methodically, scale judiciously, and remember that bio-inputs do not replace a good production system – they only enhance what is already well-designed.

Keywords: agriculture, bio-inputs, biologicals, large scale, sustainability

Sumário Executivo

Este relatório analisa o uso de bioinsumos – especialmente bioestimulantes e insumos microbianos – em sistemas de agricultura de larga escala no Brasil e no exterior, buscando separar evidências sólidas de promessas ainda em teste. A partir de revisão técnica, viagens internacionais e estudos de caso em grandes fazendas, a conclusão central é que bioinsumos já têm usos bem definidos em algumas situações (como inoculantes para leguminosas, micorrizas em solos pobres em fósforo e alguns biodefensivos), mas sua entrega em escala depende fortemente do contexto, do desenho de manejo e da governança.

O trabalho descreve três movimentos principais. Primeiro, a consolidação de usos maduros (inoculantes em soja e cana, biocontrole em alguns alvos, e certos programas de fertilizantes especiais, desenhados a partir da variabilidade da fazenda). Segundo a expansão de práticas como compostagem aditivada, biofertilizantes líquidos e consórcios microbianos, muitas vezes ligadas a modelos de fazenda circular e integração lavoura-pecuária-floresta. Terceiro, o crescimento da produção de biológicos on-farm, agora respaldada por regulamentação específica, com forte motivação econômica, mas desafios claros de padronização, qualidade e responsabilidade técnica.

Os casos visitados na América do Norte, na Europa, na Oceania e no Brasil convergem em alguns padrões. Tecnologicamente, os resultados mais consistentes aparecem quando bioinsumos são introduzidos como parte de um pacote de práticas (solo, planta, clima, logística) e não como "produto mágico". Economicamente, as soluções escaláveis são de investimento moderado, com ROI compreensível e baixa demanda por maquinário adicional. Em governança, os casos bem-sucedidos têm em comum decisões intencionais de inovar, testar em áreas-piloto, medir com rigor e escalar ou recuar de acordo com os dados, não com a narrativa comercial.

Um ponto crítico é o desenho dos testes em campo. Em grandes áreas, pequenos ganhos físicos podem se perder na variabilidade natural do talhão se não houver faixas-teste bem definidas, testemunhas claras e pelo menos duas safras de avaliação. Por isso, o relatório enfatiza que bioinsumos devem ser avaliados com métricas mais amplas do que as de sacas/ha: estabilidade interanual, margem operacional, indicadores básicos do solo e risco operacional. Sem esse rigor, as decisões acabam oscilando entre entusiasmo acrítico e rejeição prematura, gerando desperdício de tempo e de capital.

As conclusões organizam o aprendizado em três camadas: o que é robusto hoje (inoculantes, alguns biocontroles, aplicações pontuais de bioestimulantes e programas de fertilizantes especiais bem desenhados), o que é promissor (microbiologia aplicada de solo, fazendas circulares, on-farm bem estruturado) e o que ainda não sabemos (impacto econômico agregado em centenas de milhares de hectares, efeitos de longo prazo na resiliência e limites regulatórios e de mercado). A mensagem final ao produtor de grande escala é de pragmatismo informado: começar por problemas concretos, testar com método, escalar com critério e lembrar que bioinsumos não substituem um bom sistema de produção – apenas potencializam aquilo que já está bem desenhado.

Keywords: agricultura, bioinsumos, biológicos, larga escala, sustentabilidade

Table of Contents

Executive Summary **2**

Sumário Executivo **4**

List of Illustrations **7**

Preface **10**

Acknowledgments **12**

Abbreviations: **9**

1. Objectives **13**

2. Introduction **14**

2.1. Global and Brazilian Context of Large-Scale Agriculture 14

2.2. Why Biostimulants and Microbial Control Now? 14

2.3. PerResearch Question and Scope Delimitation: 14

3. Concepts, Technologies and Frontiers of Applied Microbiology **14**

3.1. What are biostimulants and biologicals? 14

3.2. Soil Microbiology in High-Productivity Systems 15

3.3. Bioinputs 15

3.3.1. Special Fertilizers: Holistic treatment 16

3.3.2. On-farm fermented products (compost tea/fertibokashi) and composting enriched with minerals and microorganisms (biocomposting) 18

3.4. Market Growth: concrete evidence of the shift 20

3.5. Scientific and Technical Evidence 21

3.5.1. What is already established (more robust benefits) 21

3.5.2. What remains promising but uncertain 22

3.5.3. Risks of hype and “snake oil”: how to separate science from marketing 22

4. Drivers, Barriers, and Economics of Large-Scale Biological Systems **22**

4.1. Global and National Drivers 22

4.1.1. Climate, biodiversity, water, and regulatory pressure 22

4.1.2. Supply chains, corporate clients, and “circularity” (adapting Steer’s Circular Farm) 23

4.2. Bio-inputs in large-scale operations 23

4.3. Barriers to Adoption in Large-Scale Systems 24

4.4. Structures enabling adoption 24

5. International Case Studies on Large-Scale Systems **25**

5.1. North America 25

5.2. Europe 26
5.3. Oceania / Other Countries 27
5.4. What these cases have in common 28
5.4.1. Technical success standards: 28
5.4.2. Patterns of economic success: 28
5.4.3. Governance and decision-making standards: 28
6. Case studies and lessons learned for the Brazilian context 28
6.1. "Large-Scale Farming" Profiles in Brazil 28
6.1.1. Grains, fibers, sugarcane, and intensive livestock farming 28
6.1.2. Decision-making structure: business groups, funds, producer-managers 31
6.2. Use cases for bio-inputs and large-scale microbiological control 31
6.3. Comparing Brazil with international cases 34
6.4. "Circular and organic farm" model. Does it make sense here? 34
6.5. On-farm biologicals 35
6.5.1. Technical limits of on-farm production. 37
6.5.2. Regulation, safety, and risk 38
6.5.3. Economic and management factors 38
7. Systems design: how to integrate biostimulants and microbiology into farm management 39
7.1. Systems design: how to integrate biostimulants and microbiology into farm management 39
7.1.1. "By design, not by default" 39
7.2. Practical Tools for the Manager 39
7.3. Scaling and Risk Management Strategies 40
7.4. Governance and decision-making elements 41
8. Conclusions 42
9. Recommendations 44
9.1. Recommendations for large-scale producers 44
9.2. Recommendations for the inputs and services industry 45
9.3. Recommendations for research, public policy, and funders 45
References 46
10. Appendices 1

List of Illustrations

Figure 1. Thiago and his GFP group visiting a dairy farm in Norway. 12

Figure 2. Specialty fertilizers, in synergy with bio-inputs and the real challenges of agriculture. 18

Figure 3. On-farm fermentation of biofertilizer using a microbial community; Americana/Três Irmãos Farm; Daniel Girello, farmer in Primavera do Leste, MT, Brazil. 19

Figure 4. Visit to a composting site and fruit plantations using sustainable management practices in the Darwin region – Northern Australia, 2022. 19

Figure 5. Biocomposting and "on-farm fertilizer" production yard at Americana/Três Irmãos Farm; Daniel Girello, farmer in Primavera do Leste, MT, Brazil. 20

Figure 6. Evolution of the global biopesticide market. 21

Figure 7. Inoculant dosages and number of companies (National Association for the Promotion and Innovation of the Biologicals Industry, 2025). 21

Figure 8. Allusion to the quackery that can plague the market. 22

Figure 9. Illustration of key points regarding the use of bio-inputs in large-scale operations. 24

Figure 10. Nuffield CSC 2019 Speaker (Iowa, USA) – Gary F. Zimmer 25

Figure 11. Gabe Brown 26

Figure 12. Engraving of John Kempf, as he prefers to present himself. 26

Figure 13. Dr. Elaine Ingham and the "Soil Foodweb" concepts. 27

Figure 14. Thiago visits a cotton farm in Kununurra, Australia, where there was strong evidence of mycorrhizae in the soil. Photo with Luke McKay, 2018 Nuffield Australia Scholar. 28

Figure 15. Survey sample distribution. Sample consistent with census data and weighted for large properties. (BCG Consulting, 2025). 29

Figure 16. Profile of Brazilian rural producers, broken down by production system, age, sustainability perspective, technology adoption, and investment preferences. Source: (BOSCHIERO, 2025), adapted from (BCG Consulting, 2025). 30

Figure 17. The 7 profiles of Brazilian rural producers, with their respective motivations and priorities in the agricultural sector. Source: (BOSCHIERO, 2025), adapted from (BCG Consulting, 2025). 31

Figure 18. On-farm biofactory at the Scheffer Group's Três Lagoas Farm in Sapezal, Mato Grosso, Brazil. 32

Figure 19. On-farm biofactory at Fartura Farm, part of the Bom Futuro Group, in Campo Verde, Mato Grosso, Brazil 32

Figure 20. Discussion among producers and experts on market trends and Regenerative Tropical Agriculture in Brazil – 5th GAAS Forum – 2025 – Sinop, MT, Brazil. 33

Figure 21. Some of Native's figures (BrasilAgro, 2018) 33

Figure 22. Circular farm concept 35

Figure 23. Innovar Group's Bioevolve on-farm equipment, featuring automation and high-quality bio-inputs 36

Figure 24. Illustration of the summary and conclusions regarding bio-inputs in large-scale agriculture. 44

Figure 25. Mind Map of Bio-inputs in Large-Scale Agriculture: From "Magic Product" to System Design 1

Figure 26. Mind Map of Bio-inputs in Large-Scale Agriculture: From "Magic Product" to System Design 2

Abbreviations:

BCG: Boston Consulting Group

CST: Contemporary Scholars Conference

EMBRAPA: Brazilian Agricultural Research Corporation

ESG: Environmental, Social and Governance

GAAS: Associated Group for Sustainable Agriculture

GFP: Global Focus Group GPS: Global Positioning System

IBGE: Brazilian Institute of Geography and Statistics

ILPF: crop-livestock-forest integration

MT: Mato Grosso (state of Brazil)

N, P and K: nitrogen, phosphorus and potassium

pH: hydrogen potential

P&D: Research and Development

POPs: Standard Operating Procedure

RNAi: ribonucleic acid interference

ROI: return on investment

Preface



Thiago Macitelli is a chemical engineer and entrepreneur with more than 25 years of experience in Brazilian industry and agribusiness, specializing in management, innovation, and sustainability. With additional training in business administration and extensive experience in large-scale cropping systems, his professional trajectory is marked by leadership in projects aimed at reconciling high productivity with more efficient and resilient agricultural practices, as reflected in his professional profile.

The Nuffield Scholarship journey, which began in 2019, was uniquely challenging and transformative. Alongside the academic commitments and international travel, Thiago faced four COVID-19 infections, a five-month hospital stay due to a postoperative infection, the birth of two children—bringing his family to four children—devotion to marriage and family, and the ongoing management of his ventures in Brazil's dynamic agribusiness market. These profound personal events not only tested his resilience but also enriched his perspective on the importance of robust production systems and holistic health—themes that resonate throughout his research.

The scholarship's extended timeframe, from 2019 to 2026, enabled a rare depth of observation and engagement. Table 1 below summarizes a selection of the main experiences and visits that underpinned this investigation, providing a global overview of bio-inputs in different large-scale contexts.

Table 1. Travel Itinerary

Travel date	Location	Visits/contacts
Mar 2019	USA	Nuffield Contemporary Scholars Conference (CSC) IOWA and farm visits
Abr 2019	Brazil	GAAS (Associated Group for Sustainable Agriculture) lecture series
Ago 2019	Brazil	3rd Brazilian Forum on Sustainable Agriculture
Mar 2020	Australia	Nuffield Contemporary Scholars Conference (CSC) Brisbane Coast Tangalooma Island Resort
Abr 2022	Netherlands / Slovakia	Farm Visits

Mai 2023	Australia	GFP: Farms, cooperatives, research institutes and logistics in Darwin and Kununurra
Mai 2023	USA	GFP: Farms, university, research institutes and agricultural industries
Mai 2023	Netherlands	GFP: Farms, bank, flower and food processing
Mai 2023	Norway	Farms, research institutes, startups and labor unions
Jun 2023	Canada	Farm Visits
Mar 2024	Brazil	Nuffield Contemporary Scholars Conference (CSC) Campo Grande MS
Ago 2024	Canada	Farms and inputs distribution stores
Jan 2025-26	Brazil	Visits to on-farm biofactories and operational properties

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Figure 1. Thiago and his GFP group visiting a dairy farm in Norway.

Objectives

The objective of this study is to analyze the role of bioinputs—such as biostimulants and microbial inputs—in large-scale agricultural systems, in Brazil and abroad, identifying in which contexts they deliver real value to producers and to the production chain.

- Map how large-scale producers in different countries are adopting bioinputs—such as biostimulants, inoculants and other biological/microbial inputs—in extensive cropping systems, and what agronomic and economic outcomes they report.
- Identify contextual factors (soil, climate, management system, management profile and technical advisory profile) that distinguish successful situations from cases in which these products fail to deliver as promised.
- Assess how input companies and technical consultancy firms are shifting from a “standalone product” logic toward integrated management approaches and holistic treatment of the production system, with a focus on large scale.
- Discuss opportunities and risks of adopting biostimulants and soil microbiology in large-scale systems in Brazil, including aspects of profitability, impact measurement, technical communication and regulation.
- Propose practical and general recommendations for producers, consultants, companies and policymakers on how to incorporate bioinputs into sustainable intensification strategies, avoiding both unfounded skepticism and uncritical enthusiasm.

1. Introduction

1.1. Global and Brazilian Context of Large-Scale Agriculture

The global population projected to reach 9.7 billion by 2050 imposes a growing demand for food, fibers and energy, putting pressure on agricultural systems to achieve higher productivity (Mariane Carvalho Vidal, 2023). In Brazil, this challenge translates into the continuous expansion and intensification of commodities such as soybean, maize, cotton and sugarcane, often on farms operating tens of thousands of hectares. This scale of operation is not only a logistical characteristic but also a determining factor that shapes technological choices, risk management and the adoption of innovations.

1.2. Why Biostimulants and Microbial Control Now?

There is a growing perception that productivity gains from conventional inputs alone are reaching a plateau, while production costs and **pressure for sustainability are increasing** (CropLife Brasil, 2026). At the same time, advances in microbiology and a deeper understanding of the rhizosphere reveal a **vast, still-unexplored potential**. Bioinputs are emerging as promising tools to increase resource-use efficiency (nutrients and water), improve stress tolerance and reduce dependence on synthetic inputs, aligning with the pursuit of sustainable intensification.

1.3. PerResearch Question and Scope Delimitation:

This report seeks to answer the central question: is the **use of bioinputs in large-scale agricultural systems** a robust strategy for gains in efficiency and resilience, or a set of solutions still limited to niches and ideal conditions? The scope is deliberately focused on large commercial farms (grains, fibers, sugarcane), where decisions are driven by risk analysis, complex logistics and clear return on investment, distancing itself from discussions that are purely theoretical or applicable only to family or organic farming.

2. Concepts, Technologies and Frontiers of Applied Microbiology

2.1. What are biostimulants and biologicals?

There is no universal definition, but there are key concepts that guide the sector. Embrapa defines bioinputs as "products, processes or technologies of plant, animal or microbial origin intended for use in agricultural production" (EMBRAPA, 2026).

CropLife Brasil and international associations often distinguish bio-pesticides (pest and disease control) from biostimulants (substances or microorganisms that improve plant metabolism, independently of their nutritional content). For this report, a broad view of

bioinputs is adopted, encompassing inoculants, biostimulants, biocontrol agents and specialty fertilizers applied at large scale.

2.2. Soil Microbiology in High-Productivity Systems

In high-productivity systems, soil is not merely a substrate but a dynamic ecosystem. Soil microbiology drives nutrient cycles (such as nitrogen and phosphorus), the formation of aggregates that improve physical structure, and the natural suppression of pathogens. Practices like well-managed no-till and crop rotation sustain this biota. When properly applied, bioinputs can act as "inoculants" or "catalysts" to modulate beneficial microbial communities, enhancing natural processes in favor of crop productivity and stability.

2.3. Bioinputs

Main categories of biological products and biostimulants (Table 2).

Table 2. Main categories of biological products and biostimulants

Type of Bioinput	Description	Sustainable impact	Example
Inoculants	Contain living microorganisms that promote biological nitrogen fixation and assist in nutrient uptake.	Reduction in the use of synthetic nitrogen fertilizers and improvement of soil health.	Application of bacteria of the genus Rhizobium to soybean seeds for biological nitrogen fixation
Biofertilizers	Products that improve soil fertility and stimulate beneficial microbiota.	Decrease in dependence on chemical fertilizers and greater biological balance of the soil.	Use of liquid or solid compounds containing organic matter and beneficial microorganisms that improve soil fertility.
Biological control agents	Organisms or natural substances that control pests and diseases in a sustainable way.	Substitution of chemical pesticides, preserving natural enemies and reducing residues.	Use of the bacterium Bacillus thuringiensis as a bioinsecticide to control caterpillars in crops such as maize and cotton.
Nutrient solubilizers	Transform nutrients that are poorly available in soil (such as phosphorus) into forms assimilable by plants.	Increase in nutrient use efficiency and reduced leaching into the environment.	Use of Bacillus megaterium to solubilize phosphorus in the soil, making it available to plants.

Bioestimulants	Substances that promote plant growth and increase tolerance to abiotic stresses.	Improvement of productivity with reduced use of synthetic inputs.	Application of humic acid or seaweed extracts to stimulate plant growth and resistance.
Semiochemicals and biochemicals	Natural compounds that influence the behavior of insects and microorganisms.	Selective pest control with lower environmental impact.	Use of synthetic sex pheromones in traps to attract and monitor pests such as the tomato leafminer.
Bio-inputs for animal and aquaculture production	Products used to improve the health and nutrition of aquatic animals and organisms.	Promotion of animal welfare and reduction of antibiotic use.	Incorporation of probiotics into fish diets in aquaculture systems to improve intestinal health and weight gain.
Post-harvest technologies	Biofilms and compounds that reduce losses and extend the shelf life of agricultural products after harvest.	Reduced food waste and loss reduction in the agri-food supply chain.	Application of edible biofilms to fresh fruits, such as apples or mangoes, to extend their post-harvest shelf life.

2.3.1. Special Fertilizers: Holistic treatment

The recent expansion of the “special fertilizers” market — which includes microbial inoculants, biostimulants, humic and fulvic acids, seaweed extracts and highly concentrated foliar blends — has created a new set of possibilities and risks for large-scale systems.

In theory, these inputs promise to improve the efficiency of N, P and K use, reduce losses by volatilization and leaching, increase root growth, modulate the plant hormonal balance and make the system more resilient to biotic and abiotic stresses. In practice, however — especially on farms of tens of thousands of hectares — adoption takes place in an environment of high operational complexity, large soil and climate variability and strong pressure for short-term results. It is precisely at this intersection between technological promise and field reality that the concept of a “holistic treatment” of fertility and biostimulation becomes critical.

From a biological standpoint, many special fertilizers act through relatively specific mechanisms: supplying easily accessible carbon, complexing nutrients, hormonal stimulation during sensitive windows of the crop cycle, increasing microbial activity in the rhizosphere, or mitigating stresses such as drought, waterlogging and phytotoxicity.

In controlled, small-scale environments these mechanisms are easier to isolate, test and adjust. On large farms, however, the same products need to “talk” to a series of other

factors: different management histories, contrasts in soil texture and depth, narrow operational windows, application quality, tank logistics, mixing and refilling, in addition to coexisting with mineral fertilization programs, pesticides and growth regulators. The agronomic potential of the input, in isolation, becomes only part of the equation.

There is also a clear economic and risk-management dimension. Special fertilizer programs are often presented as high-return investments, with promises of productivity increases or nutrient-use efficiency far above average.

On large-scale properties, however, small differences in physical response (for example, a few bags per hectare more or less) can be diluted by the field's natural variability and be difficult to detect with statistical confidence, especially when the experimental design is weak or nonexistent. At the same time, the cost per hectare, when multiplied across tens of thousands of hectares, quickly becomes a significant budget item. This requires greater discipline in hypothesis definition, test-strip design and variable control, as well as a careful interpretation of results across multiple seasons.

Another sensitive point is managing expectations regarding the role of these inputs in the system. Special fertilizers, however sophisticated, do not replace liming to correct acidity, compaction management, crop rotation, well-sized base fertilization or soil cover. When used in an attempt to compensate for structural system failures — for example, trying to "correct by foliar" chronic fertility deficiencies or physical soil problems — the likelihood of frustration is high.

Several of the experiences visited show that where the agronomic base is weak, biostimulants and adjuvants rarely deliver the promised result, because they attempt to "push" a structurally limited system. Conversely, where there is already consistent effort in rotation, soil cover, organic matter management and adequate chemical correction, these inputs can act as fine levers for efficiency or resilience gains. At large scale, therefore, the key question ceases to be "which product works?" and becomes "in what agronomic and management context does this type of input make sense, with what measurable objective and with what decision design?".

A concrete example of this logic is the work of Brazilian companies that aim to design special fertilizer programs targeted at large Central-West properties, integrating different mechanisms of action instead of betting on a single product (Figrure 2).



Figure 2. Specialty fertilizers, in synergy with bio-inputs and the real challenges of agriculture.

The companies: **NVA-NOVAAG**—headquartered in São Paulo with facilities in Mato Grosso, Goiás, and Minas Gerais—and **AMBIOS**—based in Mato Grosso—operate in this space, for example, by developing programs based on farm variability maps and clear agronomic objectives for each environment (such as stabilizing production in sandier areas, maximizing yield potential in fertile low-lying areas, or mitigating the impact of recurring water deficits in specific plots).

Based on this diagnosis, the "specialty fertilizer" package is structured by combining carbon sources, complexing agents, biostimulants, micronutrients, and—where appropriate—bio-based solutions, all grounded in soil and plant data as well as management history. Initiatives of this kind, characterized by a holistic, systems-oriented approach, have demonstrated not only agronomic gains but also consistent adoption growth among large-scale producers—precisely because they address the genuine complexities of large farming operations rather than offering simplistic solutions to complex problems.

2.3.2. On-farm fermented products (compost tea/fertibokashi) and composting enriched with minerals and microorganisms (biocomposting)

On-farm fermented products, such as compost tea and fertibokashi, are artisanal or semi-artisanal preparations that utilize the controlled fermentation of organic materials (manure, brans, molasses) to multiply beneficial microorganisms and generate bioactive compounds. Their underlying principle is the rapid introduction of a diverse microbial community into the soil or onto the plant.

Large-scale use faces challenges regarding standardization, quality control, and production logistics; however, it represents a trend toward producers taking ownership of the biological process, thereby reducing costs and increasing autonomy (Figure 3).



Figure 3. On-farm fermentation of biofertilizer using a microbial community; Americana/Três Irmãos Farm; Daniel Girello, farmer in Primavera do Leste, MT, Brazil.

Biocomposting is a form of composting enhanced with minerals and microorganisms; it involves the decomposition of organic waste combined with mineral sources (such as rock dust, natural phosphates, or micronutrients) and specific microbial inoculants, aiming to accelerate the process, increase compost stability, and enrich its nutritional value for plants (Figure 4).



Figure 4. Visit to a composting site and fruit plantations using sustainable management practices in the Darwin region – Northern Australia, 2022.

Despite its great potential to improve soil fertility and nutrient use efficiency, its large-scale use in agriculture faces significant challenges, such as the need for stricter control of process conditions, additional costs for inputs and inoculants, the demand for specialized technical knowledge, difficulty in standardizing quality across large volumes, and logistical barriers regarding production, transport, and application in extensive agricultural systems (Figure 5).



Figure 5. Biocomposting and "on-farm fertilizer" production yard at Americana/Três Irmãos Farm; Daniel Girello, farmer in Primavera do Leste, MT, Brazil.

2.4. Market Growth: concrete evidence of the shift

The global biostimulant market is projected to grow from USD 3.2 billion in 2022 to USD 5.6 billion by 2027, at a compound annual growth rate (CAGR) of 11.9% (INSPER, 25). In Brazil, the biopesticide market generated R$ 2.3 billion in the 2022/23 crop season—marking growth of over 40% compared to the previous cycle—and is expected to reach R$ 4.9 billion by 2030 (Secretariat of Agricultural Defense, 2025).

In China, government policies aimed at reducing chemical fertilizer use are driving the sector, while in Australia, adoption is motivated by soil health and drought challenges. Figure 6 illustrates the evolution of the global biopesticide market.

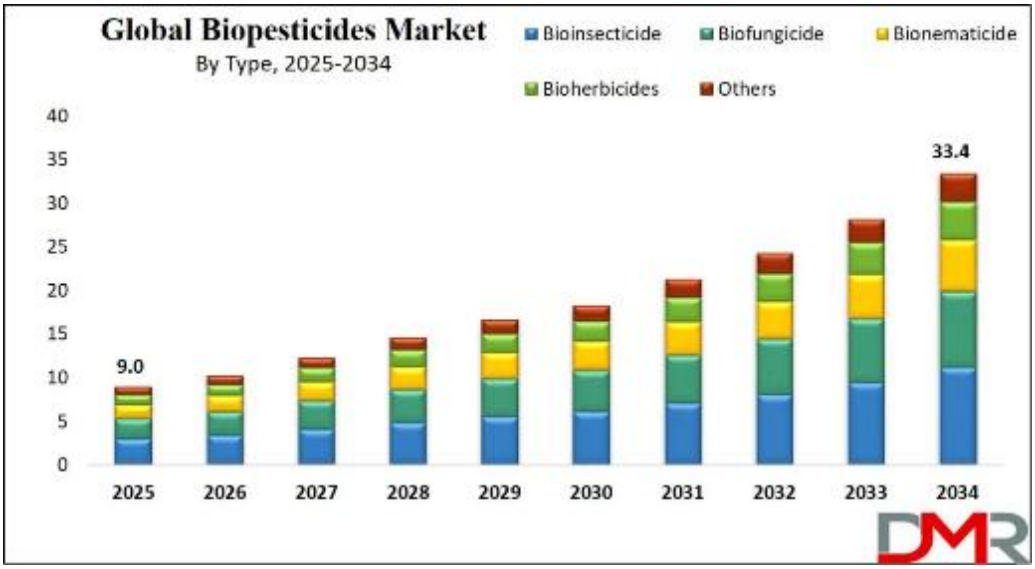

Figure 6. Evolution of the global biopesticide market.

2.5. Scientific and Technical Evidence

2.5.1. What is already established (more robust benefits)

Biological nitrogen fixation in soybeans using rhizobial inoculants is a fully established technology—backed by decades of use and massive application volumes—that saves billions in nitrogen fertilizers in Brazil. Inoculants for sugarcane (for example, those containing bacteria such as *Gluconacetobacter diazotrophicus*) also have solid evidence supporting increased productivity. Biocontrol agents such as *Bacillus thuringiensis* (Bt) and *Trichoderma harzianum* have proven efficacy against caterpillars and certain soil pathogens, respectively, and are widely used (Figure 7).

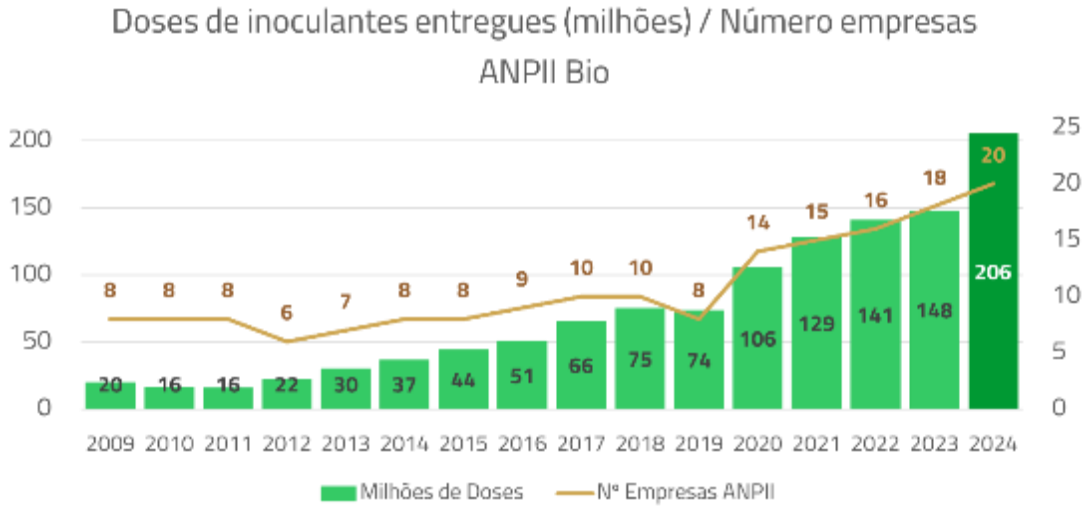

Figure 7. Inoculant dosages and number of companies (National Association for the Promotion and Innovation of the Biologicals Industry, 2025).

2.5.2. What remains promising but uncertain

RNA interference (RNAi)-based technologies for gene silencing in pests, the use of specific microbial metabolites (rather than the live microorganism), and the topical application of hormones or hormone precursors synthesized via biotechnological pathways represent cutting-edge areas. While promising high specificity and a novel mode of action, they face challenges regarding production costs, field stability, regulation, and the potential for resistance, and currently remain in the advanced research or initial launch phase.

2.5.3. Risks of hype and “snake oil”: how to separate science from marketing

The market's rapid growth attracts exaggerated claims. Distinguishing science from marketing requires examining the consistency of results across multiple growing seasons and locations, as well as the existence of long-standing partnerships between companies and leading growers. Products that gain a solid foothold typically feature a clear mechanism of action, well-defined usage protocols, and research data from independent sources (such as universities or public institutes). A culture of agricultural extension and rigorous on-farm experimentation—testing on a small scale before scaling up—is the grower's primary tool for mitigating this risk. Figure 8 alludes to the quackery that can plague the market.



Figure 8. Allusion to the quackery that can plague the market.

3. Drivers, Barriers, and Economics of Large-Scale Biological Systems

3.1. Global and National Drivers

3.1.1. Climate, biodiversity, water, and regulatory pressure

Climate change increases the frequency of abiotic stresses (such as drought and heat), driving demand for solutions that enhance plant resilience—a key role played by biostimulants. Biodiversity loss and the contamination of water resources by agrochemicals are generating social and regulatory pressure for cleaner practices.

In tropical climates like Brazil's, which allow for multiple annual harvests, vegetation remains active in the fields year-round (a phenomenon known as the "green bridge"). This "green bridge" fosters disease and insect pressure. In this context, bio-inputs—particularly biological crop protection products—are viewed as tools for resistance management and residue reduction, often used alongside chemical controls to maximize and prolong control efficacy.

3.1.2. Supply chains, corporate clients, and “circularity” (adapting Steer’s Circular Farm)

Major commodity buyers (trading companies, food manufacturers) are establishing ESG and traceability criteria, creating a commercial driver for sustainable practices.

The concept of the "circular farm"—which seeks to close nutrient and energy cycles within the property (for example, by using waste to produce biofertilizers)—is gaining momentum as a model that reduces costs associated with external inputs, increases autonomy, and meets these market demands, as explored in Charlie Steer’s report (Steer, 2021).

3.2. Bio-inputs in large-scale operations

For large-scale farms, the adoption of any technology is an equation that balances cost, risk, and return on investment (ROI).

Bio-inputs must compete not only on the basis of agronomic efficacy but also on logistics and operational integration.

Operating at scale already entails high fixed costs for personnel and machinery; biological solutions must be designed to create synergies with existing processes—such as tank-mixing with foliar fertilizers, industrial seed treatment, or pre-plant burndown—thereby maximizing the use of available infrastructure. Figure 9 illustrates the key points of application for bio-inputs in large-scale operations.

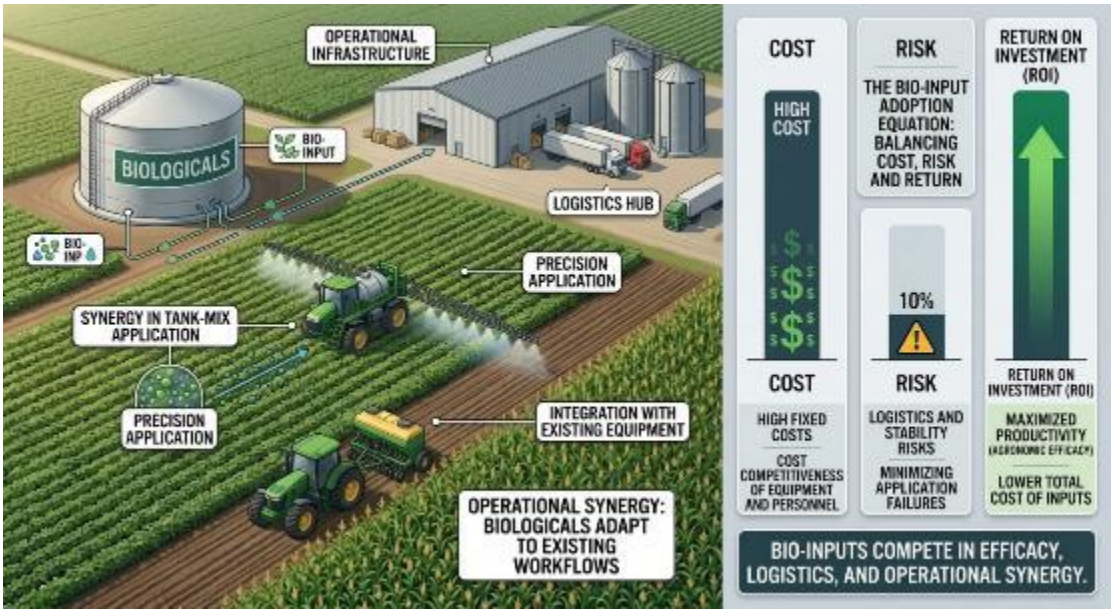

Figure 9. Illustration of key points regarding the use of bio-inputs in large-scale operations.

3.3. Barriers to Adoption in Large-Scale Systems

Large-scale operations are complex machines, with pre-established processes for planting, application, and harvesting.

The introduction of bio-inputs—which may entail specific requirements regarding storage, mixing, application timing, and equipment—adds a layer of complexity that can be viewed as an operational cost.

Furthermore, technical skepticism persists due to the variability of responses and the relative scarcity of independent, large-scale, replicable data. This skepticism is compounded by conflicting incentives along the supply chain, where resellers and consultants may derive greater profitability from selling conventional inputs.

Paradoxically, this critical barrier also has a positive side: it drives a gradual, results-based consolidation, preventing the uncritical adoption of fads.

3.4. Structures enabling adoption

Successful adoption at scale often emerges from collaborative structures:

- On-farm R&D programs—such as the Dakota Lakes Research Farm model in the U.S., where producers co-finance and validate applied research—are powerful.
- Producer groups and experience-sharing networks, such as BASE in the USA
- Groups of experts, enthusiasts, and producers: GAAS (Associated Group for Sustainable Agriculture) in Brazil, which operates on the principle of “farmer-to-farmer education,” building trust and accelerating learning.

Finally, structured partnership models involving industry, research, and producer groups—featuring clear governance and the sharing of data and risks—prove effective for developing and validating solutions tailored to specific realities.

4. International Case Studies on Large-Scale Systems

4.1. North America

In the U.S., the integration of biologicals into no-till and living-cover cropping systems is an expanding strategy. Gary Zimmer, a consultant and founder of Midwestern BioAg, advocates a "balanced nutrition" approach that includes inoculants and minerals to "feed the soil." His recommendations for large-scale farms focus on correcting mineral imbalances as the foundation for active biology (Figure 10).

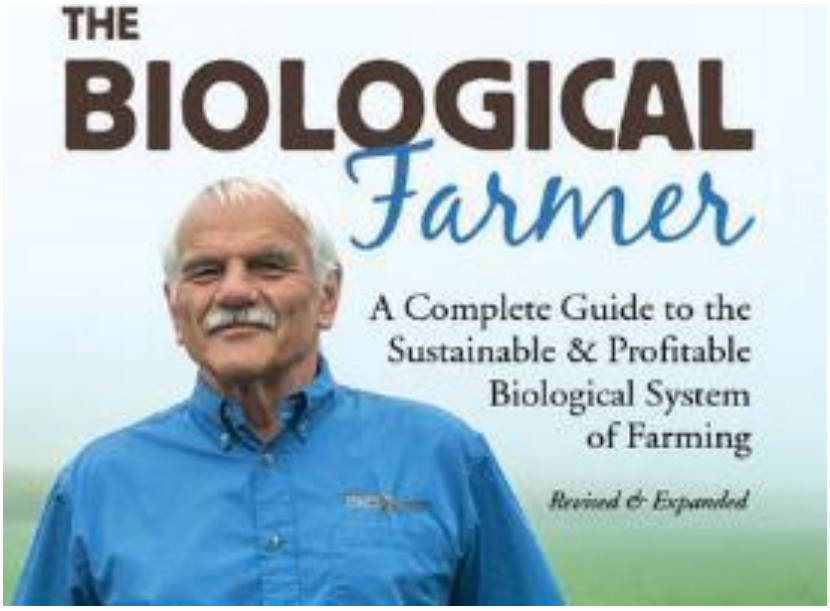

Figure 10. Nuffield CSC 2019 Speaker (Iowa, USA) – Gary F. Zimmer

Gabe Brown, a regenerative agriculture icon in North Dakota, demonstrated on his farm how extreme diversification (up to 70 cover crop species) and the elimination of synthetic inputs rebuild soil health, drastically reducing the need for fertilizers (Figure 11). He uses his own composts and extracts (such as compost tea) as biostimulants within this complex system.

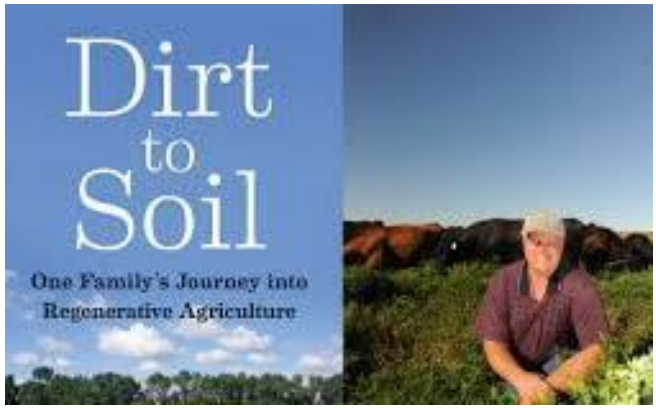

Figure 11. Gabe Brown

John Kempf, founder of "Advancing Eco Agriculture," focuses on the "physiological nutrition" of plants to enhance their natural resistance. His work with large-scale fruit and grain growers employs targeted foliar applications of minerals, amino acids, and biological compounds to optimize photosynthesis and plant immunity, often reducing the need for fungicides. Figure 12 shows the illustration used by this grower.



Figure 12. Engraving of John Kempf, as he prefers to present himself.

4.2. Europe

The Soil Food Web, a concept popularized by Dr. Elaine Ingham, advocates for the massive inoculation of soils with specific microbial consortia to restore ecosystem functions (Figure 13).

While the large-scale application of its protocols is complex, its principles influence practices such as compost tea production and the enhancement of soil biota.

In European practice, "lighthouse" farms operating on a commercial scale using circular models stand out. Dowth Farm—the world's first carbon-neutral beef cattle farm—in Ireland, studied by Nuffield Scholar Charlie Steer (Steer, 2021), and the Maj family operation in Sweden are examples that integrate livestock, grain production, and waste processing within closed-loop systems, utilizing biofertilizers and biological management as central elements of their economic models.



Figure 13. Dr. Elaine Ingham and the "Soil Foodweb" concepts

4.3. Oceania / Other Countries

In Australia, the focus on soil microbiology is driven by ancient, nutrient-poor soils as well as recurring droughts.

Case studies from large grain and pasture operations in the wheat belt demonstrate the adoption of forage legume inoculants and mycorrhizal fungi to improve water and phosphorus uptake in sandy soils.

The clear lesson is that the solutions that "scale" are those addressing a critical, high-cost production bottleneck (such as phosphorus fertilization), whereas highly complex approaches or those requiring radical management changes see slower adoption.

During a visit to a large farm in Australia's Northern Territory, it was possible to observe challenges similar to those found in the Brazilian Center-West—such as distance and logistics, the adaptation of management practices to local circumstances, and great dedication to the work.



Figure 14. Thiago visits a cotton farm in Kununurra, Australia, where there was strong evidence of mycorrhizae in the soil. Photo with Luke McKay, 2018 Nuffield Australia Scholar.

4.4. What these cases have in common

4.4.1. Technical success standards:

Holistic experimentation and gradual adoption: successful cases begin with a diagnosis of the system as a whole (soil, plant, climate) and test bio-inputs as part of an integrated strategy, rather than as isolated solutions. Adoption is incremental, starting with specific areas or problems.

4.4.2. Patterns of economic success:

Low- to moderate-investment initiatives: the interventions that spread most widely are those with moderate upfront costs and a clear ROI (even if long-term), and which do not require heavy investment in new machinery.

4.4.3. Governance and decision-making standards:

The decision to innovate and review processes: behind every case lies a manager or group willing to question established practices, invest in monitoring (soil, biological, and plant analyses), and empower their team to manage the new complexity.

5. Case studies and lessons learned for the Brazilian context

5.1. "Large-Scale Farming" Profiles in Brazil

5.1.1. Grains, fibers, sugarcane, and intensive livestock farming

Brazil is home to some of the world's largest agricultural operations. In Mato Grosso, the country's leading producer, soybean and cotton farms frequently exceed 10,000 hectares, with significant average sizes.

Companies such as SLC Agrícola, Bom Futuro, Scheffer, and Grupo Roncador hold portfolios totaling hundreds of thousands of hectares. In the sugar-energy sector, mills operate their own sugarcane plantations that can range from 30,000 to over 100,000 hectares.

According to the IBGE Census of Agriculture (2017), only 1% of rural establishments exceed 1,000 hectares, yet they account for approximately 47% of the country's agricultural land.

Figure 15 shows data from a census conducted by BCG Consulting (2025).

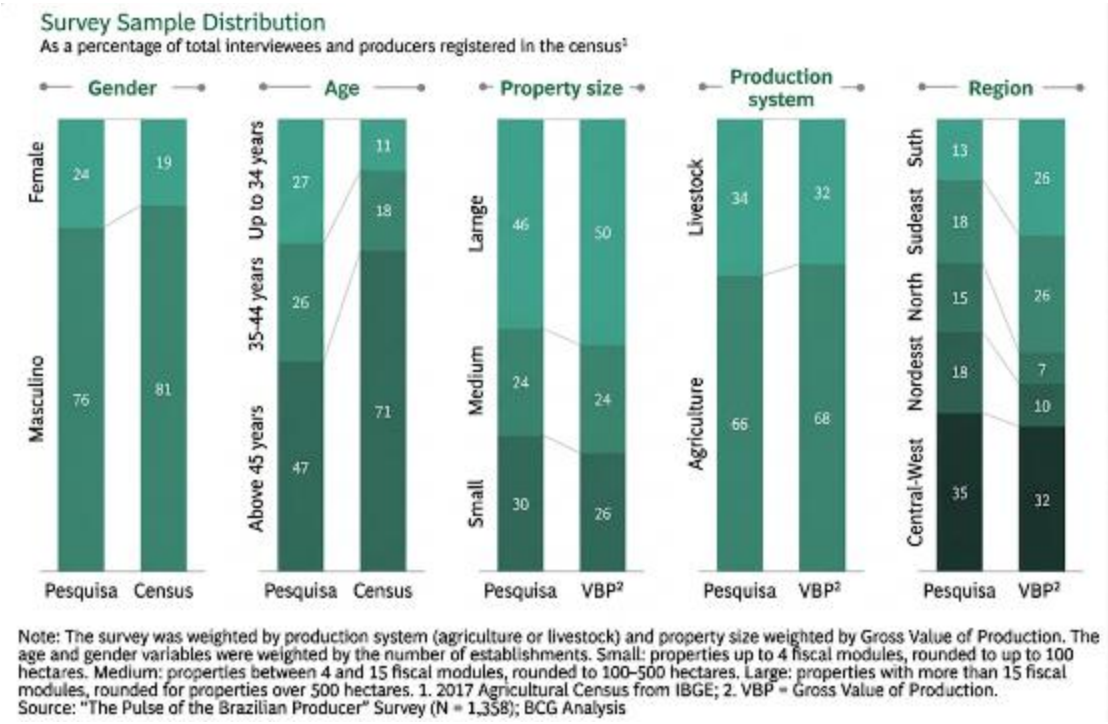

Figure 15. Survey sample distribution. Sample consistent with census data and weighted for large properties. (BCG Consulting, 2025).

According to a 2025 BCG Consulting report, approximately 46% of Brazilian farmers operate on land exceeding 500 hectares, a scale that characterizes so-called corporate agribusiness. These operations are predominantly family-owned but feature professional management, planned succession, and the intensive use of technology.

Practices such as no-till farming (97%), crop rotation (93%), and the use of inoculants (72%) have already become standard. There is growing concern regarding traceability, certification, and carbon, driven by the demands of international exporters and consumers. Large producers are leading the adoption of low-carbon and pasture restoration programs but still face challenges in monetizing these assets (e.g., carbon credits).

According to this same survey, the behavioral profile of these farmers is divided as shown in Figure 16.



Figure 16. Profile of Brazilian rural producers, broken down by production system, age, sustainability perspective, technology adoption, and investment preferences. Source: (BOSCHIERO, 2025), adapted from (BCG Consulting, 2025).

This diversity of profiles reflects the need for approaches tailored to each producer. Regarding the adoption of new technologies, for instance, the study showed that only 18% of producers consider themselves among the first to use them. Segmenting these users is, therefore, crucial for the implementation and success of new technologies (BOSCHIERO, 2025). Figure 17 presents the seven profiles of Brazilian producers.

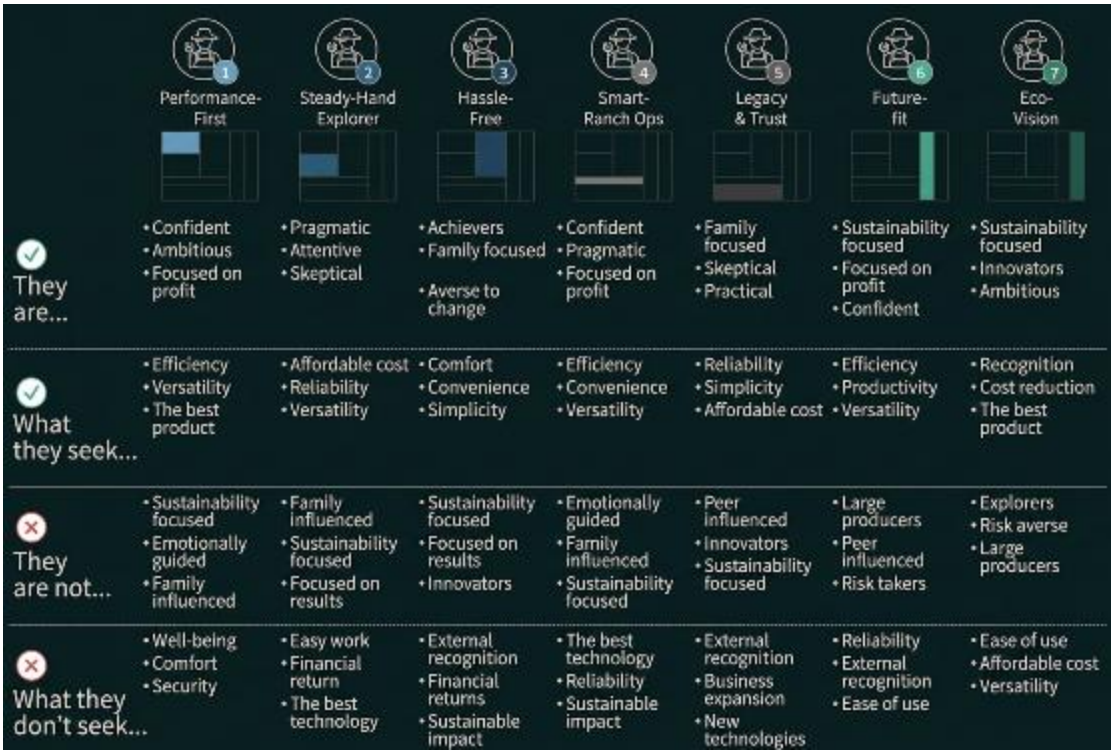

Figure 17. The 7 profiles of Brazilian rural producers, with their respective motivations and priorities in the agricultural sector. Source: (BOSCHIERO, 2025), adapted from (BCG Consulting, 2025).

5.1.2. Decision-making structure: business groups, funds, producer-managers

Decision-making within large groups follows corporate logic. In publicly traded companies or investment funds, there is strong pressure for quarterly financial results and formalized risk assessments.

In large family-owned groups (such as many in the Midwest), decision-making can be more agile, yet it remains centralized within a technical board or with the owner-manager. In all cases, the adoption of innovations—such as bio-inputs—is subject to a cost-benefit analysis and an assessment of operational impact.

5.2. Use cases for bio-inputs and large-scale microbiological control

- **Scheffer Group:** Field reports indicate that the group employs a structured program using microbial inoculants (Rhizobium and Azospirillum) and biostimulants across its vast soybean and corn acreage. Insights gained center on the logistics of industrial-scale application and the need for continuous monitoring to economically validate the results, which have been positive in terms of yield stability. The group's bio-factory is shown in figure 18.



Figure 18. On-farm biofactory at the Scheffer Group's Três Lagoas Farm in Sapezal, Mato Grosso, Brazil.

- **Bom Futuro Group:** As the sponsor of this grant, the group is known for its innovative approach. Available information suggests advanced experimentation with various categories of bio-inputs, ranging from biopesticides to organo-mineral fertilizers and inoculants. Their insights are strategic, focusing on integrating these tools into a high-productivity, low-cost business model. The group's bio-factory is shown in Figure 19.



Figure 19. On-farm biofactory at Fartura Farm, part of the Bom Futuro Group, in Campo Verde, Mato Grosso, Brazil

- **Sustainable Agriculture Associates Group (GAAS):** This network of producers and enthusiasts functions as a living laboratory for exchange. Experiences shared within GAAS demonstrate a pragmatic approach to adoption: biological products

are used where they offer a clear advantage (e.g., biological nematicides, *Trichoderma* on seeds), while other areas still rely on conventional solutions. The primary limitation reported is the inconsistency of results across different environments. Figure 20 shows a discussion among producers at a major event in the city of Sinop, Mato Grosso.



Figure 20. Discussion among producers and experts on market trends and Regenerative Tropical Agriculture in Brazil – 5th GAAS Forum – 2025 – Sinop, MT, Brazil.

- **Leontino Balbo (Native / Balbo Group):** A pioneer in the sugarcane sector, Balbo developed a proprietary large-scale organic and microbial fertilization system, drastically reducing the use of synthetic fertilizers. While his case is extreme and specific, it demonstrates the technical and economic feasibility of a radical biological transition, provided there is investment in in-house R&D and a complete shift in management paradigms. Selected production data for this group are presented in Figure 21.



Figure 21. Some of Native's figures (BrasilAgro, 2018)

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5.3. Comparing Brazil with international cases

Data from CropLife Brazil and specialized consultancies position the country as a global leader in the adoption of biopesticides, though the use of biostimulants and inoculants for crops other than soybeans is still in a growth phase.

Brazil's greatest comparative advantage lies in its tropical climate—which fosters microbial activity—its vast area under no-till farming (which preserves soil biota), and its dynamic bio-input industry. However, this same climatic factor can sometimes be viewed as a limitation; the environment promotes the proliferation of pathogens and insects, driving high demand for chemical pesticides and making it difficult to implement 100% organic management practices on very large farms.

A specific risk is the temptation to seek "silver bullets"—miracle products—without investing in whole-system management; this approach leads to frustration and hinders consistent adoption.

Furthermore, the scale of large agricultural operations allows for the observation of bio-inputs under a wide range of conditions.

5.4. "Circular and organic farm" model. Does it make sense here?

The concept of the circular farm in Brazil involves applying circular economy principles to agricultural production, aiming to close nutrient cycles, reduce waste, and promote the efficient use of natural resources. Instead of a linear model (extract-produce-discard), the circular farm integrates various activities and waste streams, transforming what would be waste into inputs for other production processes. This can involve, for example, composting organic waste, implementing crop-livestock-forestry integration (ILPF), utilizing animal manure to generate biogas and biofertilizers, and reusing water.

A large-scale Brazilian circularity model must integrate the following (Figure 22):

1) Short nutrient loops: composting on-farm waste (crop residues, poultry litter, filter cake), producing biofertilizers from crop-livestock integration waste, and utilizing local industrial by-products (such as those from ethanol plants).

2) Crop-livestock-forestry integration (ILPF) with bio-inputs: Rotating crops with pastures and trees improves soil quality, and applying inoculants to forage and crops can further enhance these benefits.

3) Ecosystem services: A well-managed circular system generates carbon credits and improves water infiltration, opening doors to new markets and green financing.

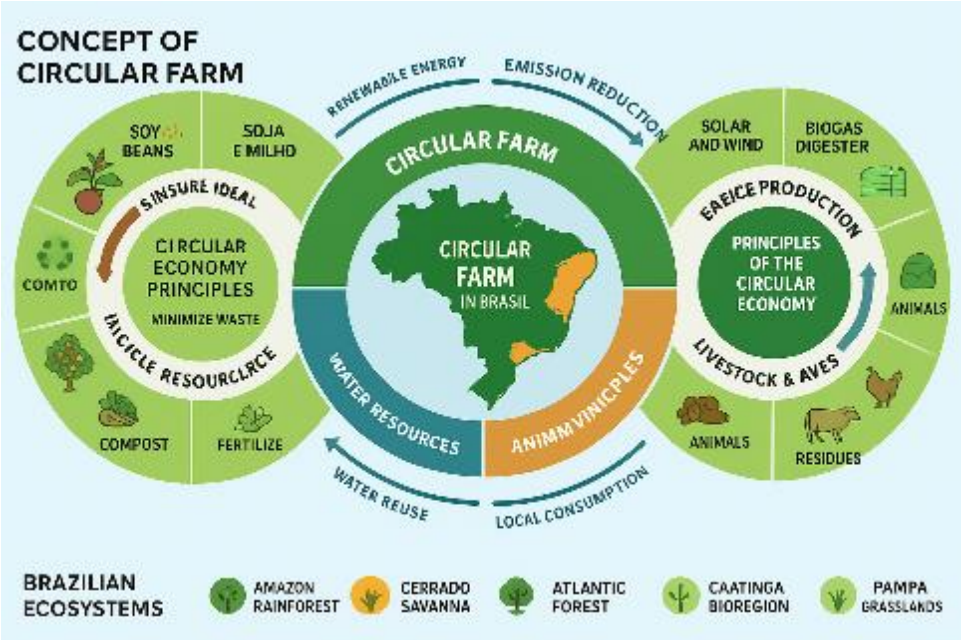

Figure 22. Circular farm concept

Concrete examples of this model already exist in Brazil. Some large-scale farms, such as those belonging to the Fazenda da Toca Group (São Paulo), employ agroforestry systems, large-scale composting, and the integration of poultry, vegetables, and perennial crops, thereby closing nutrient cycles and reducing the need for external inputs. Another example is the use of biodigesters on dairy farms in the South and Southeast regions, where animal waste generates electricity for the farm and biofertilizer is returned to the fields. In the sugar-energy sector, mills such as Raízen reuse vinasse and filter cake as fertilizers, in addition to investing in energy cogeneration from sugarcane residues.

5.5. On-farm biologicals

A Structural Trend or Just a Fad? On-farm production of biologicals, such as *Bacillus* and *Trichoderma*, has a history in Brazil, initially linked to organic farming.

Its recent evolution—featuring more robust equipment and more standardized protocols—is attracting large-scale producers due to cost reductions and greater autonomy (Figure 22).



Figure 23. Innovar Group's Bioevolve on-farm equipment, featuring automation and high-quality bio-inputs.

Despite challenges regarding quality control and regulation, the economic incentive is strong. Therefore, rather than a passing fad, this is a structural trend poised for growth—particularly concerning microorganisms with broader applications and for farms possessing the technical infrastructure to manage the process.

This trend is so significant in Brazil that it necessitated the regulation of "on-farm" bio-input production. This was formalized through the approval of Law No. 15.070/2024, which authorizes and establishes rules for farmers to produce biological inputs for their own use. The new legislation provides a legal framework for the practice, distinguishing bio-inputs from conventional pesticides while aiming to ensure product quality and food safety. These regulations address the previous landscape, which had created legal uncertainty surrounding the practice (Gusmão, 2025). Key aspects of the regulations governing "on-farm" biologicals in Brazil are outlined in Table 3.

While on-farm production is a powerful practice with significant growth potential, it is unlikely to fully replace high-tech industrial products due to certain structural factors.

Table 4. Key aspects of the regulation of "on-farm" biologicals in Brazil

Personal Use and Commercialization:	On-farm production is permitted exclusively for personal use within the same property or properties belonging to the same economic group or cooperative; commercialization is prohibited.
Exemptions and Registration:	Products produced on-farm are exempt from registration, but producing establishments must complete a simplified registration with the Ministry of Agriculture and Livestock (MAPA).

Source of Biological Material:	The use of strains from accredited germplasm banks or products containing strains registered for this purpose is permitted. The use of commercial products (purchased bactericides/fungicides) as an inoculum source (subculturing) is prohibited.
Best Practices and Responsibility:	The producer must follow good practice standards established by MAPA, which include the requirement for a qualified technical supervisor.
Inspection	Failure to comply with the rules may result in fines, seizure of products, and closure of the property.

5.5.1. Technical limits of on-farm production.

A) Variability and standardization

On-farm: each farm has different water, equipment, strains, management practices, and hygiene standards. This results in batches with highly variable microorganism concentrations, purity, and performance.

Industrial: there is fine process control (fermenters, sensors, control of temperature, pH, oxygen, and defined culture media), ensuring products with standardized concentration, purity, and stability. For certain critical applications (e.g., seed treatment with precise dosages or the application of biologicals at very low rates), this standardization is essential.

B) Formulation complexity

Many "high-tech" biologics are not just microorganisms: they are complex formulations with:

- Blends of selected strains,
- Encapsulation prototype (polymers, microcapsules, UV protectants, adhesion agents, surfactants),
- Stabilizers that extend shelf life and ensure viability even under adverse conditions.
- Replicating this level of formulation on the farm is very difficult, expensive, and, in practice, unfeasible on a large scale. On-farm production tends to focus more on simple solutions (inoculants, liquid biofertilizers, live microbial suspensions) than on sophisticated formulations.

C) Stability and shelf life

- High-tech industrial products are developed to have a long shelf life (months, sometimes years) under varied storage conditions.
- On-farm production typically involves short-shelf-life products that must be used shortly after production. This limits logistics, the application window, and scalability.

D) Scope of application

Some biologicals or bio-inputs require specific infrastructure (large-scale fermenters, complex downstream processing, purification, drying, freeze-drying, encapsulation) that

is not economically viable at the farm level. Certain products will simply never be economically feasible for on-farm production.

5.5.2. Regulation, safety, and risk

A) Responsibility and health risk

- On-farm production involves handling microorganisms. If cross-contamination occurs (unwanted fungi, pathogens, endotoxins), the risks include: loss of efficacy; crop damage; and environmental or even human health risks.
- The industrial model involves rigorous biosafety protocols, process validation, and laboratory quality testing. → Regulators tend to be more restrictive regarding the unchecked expansion of on-farm production, precisely because of the risk of misuse..

B) Increasing legal requirements

Although current regulations are straightforward, the legislative trend—as seen with biologicals and pesticides in general—is toward stricter requirements for traceability, quality control, and proof of efficacy.

This is easier to demonstrate for well-structured companies that possess laboratories, regulatory teams, and auditable processes. On-farm production is likely to remain permitted, albeit subject to limitations (such as restrictions on use, product categories, and production volumes)..

C) Civil liability and insurance

- In the event of a problem (e.g., pest control failure, environmental damage, unwanted residue), it is much easier to assign liability for a registered industrial product.
- On-farm production places more risk directly on the producer, which can be a sensitive issue for large groups that rely on insurance, banks, and environmental compliance.

5.5.3. Economic and management factors

A) Hidden operating cost

At first glance, on-farm production seems “cheaper” because the producer “does it in-house,” but there are hidden costs such as:

- Skilled labor,
- Equipment (tanks, pumps, aeration systems, filtration, etc.),
- Energy,
- Culture inputs,
- Minimum quality control (basic analyses).

At certain scales and in certain cultures, the total cost may not be as advantageous as purchasing a ready-made industrial product, especially if there are losses resulting from process failures.

B) Management complexity

On-farm production requires the producer to also become a small-scale manufacturer, introducing new activities into their routine that fall outside their core focus—and often their area of expertise: planning batches, ensuring quality, documenting processes,

training staff, managing cash flow, and keeping the team motivated to live and work in a rural setting.

Many producers prefer to focus their efforts on crop and market management, outsourcing technological solutions to the industry.

C) Continuous innovation

High-tech industrial products undergo constant research and development—involving new strains, new formulations, and new modes of action. On-farm production tends to rely on established technologies—often derived from public research—characterized by slower, incremental innovation. To remain at the technological frontier (e.g., engineered microbial consortia, RNAi, bioherbicides, advanced formulations), the industry must maintain its relevance.

6. Systems design: how to integrate biostimulants and microbiology into farm management

6.1. Systems design: how to integrate biostimulants and microbiology into farm management

6.1.1. "By design, not by default"

Successful integration requires intentional planning ("design"), rather than the mere random substitution of one input for another. This means defining clear objectives (e.g., improving nitrogen efficiency, reducing water stress) and selecting biological tools that align with this broader strategy.

Thinking in terms of cycles rather than lines: one of the major challenges is shifting the mindset from a production-line approach (input → plant) to one based on processes and cycles (residue → soil → biota → plant → residue). This entails mapping carbon, nutrient, and water flows across the farm and identifying points where bio-inputs can optimize or close these cycles, thereby reducing losses and external costs.

6.2. Practical Tools for the Manager

How to rigorously test biostimulants in the field (using a simple yet robust experimental design): Use wide, long test strips (to minimize edge effects), with within-plot replicates and an absolute control (an area without the product). Collect yield data via GPS and perform basic statistical analysis. Test over at least two growing seasons before making a decision to scale up..

It is **important** to recognize that agriculture is an activity characterized by high variability and that academic research traditionally focuses on isolating specific factors. In the case of biological inputs, isolating factors carries the risk of yielding only minor results; the search for a "silver bullet" fails to deliver satisfactory outcomes, leading to frustration. Therefore, it is important to consider synergistic sets of practices that foster more sustainable management, such as:

- Implement the use of foliar-applied biological products, while ensuring that weather conditions and tank-mix compatibility are suitable.

- Understand synergies and antagonisms (e.g., applying microbial inoculants to soils with good organic matter content and corrected pH enhances their effect).
- Select plant genetics that respond well to the presence of mycorrhizae.
- Apply foliar biostimulants during key physiological stages (e.g., stem elongation, grain filling) determined by crop management practices.

Minimum metrics: beyond productivity (bags/ha), it is necessary to broaden the scope of understanding to include benefits that may prove more advantageous than the productivity result achieved, such as:

- Stability (lower year-to-year variability);
- Operating margin (cost of the bio-input vs. productivity gain or savings on another input);
- Soil indicators (organic carbon, microbial respiration);
- Operational risk (ease of application, compatibility).

6.3. Scaling and Risk Management Strategies

Start small and scale up: This model of caution and gradual implementation was thoroughly discussed by Nuffield researcher Byrne (2019).

Allocate a small percentage of the total area (5–10%) to an integrated pilot program. Learn, adjust protocols, and only then expand to larger areas, plot by plot.

Typical errors in large-scale adoption: The dynamic nature of large-scale operations, combined with labor constraints, often leads to common mistakes—such as failing to calibrate equipment for varying volumes, mixing incompatible products in the tank, or applying products under unsuitable environmental conditions. To mitigate these and other issues, planning and team engagement are essential, alongside the implementation of simple staff training processes, written operating procedures (SOPs), and preliminary compatibility tests.

When it makes sense to internalize (Make) versus outsource (Buy) biological solutions: for large farms, the choice between on-farm biological production and purchasing ready-made industrial solutions is less an ideological issue and more a decision regarding risk management and resource allocation.

Internalizing the production of bio-inputs becomes viable when a farm operates at a significant scale and possesses a stable technical team and a degree of process standardization (such as SOPs, quality control, and record-keeping).

In such contexts, producing some biologicals on-farm can lower unit costs per hectare, ensure availability during critical windows, and allow formulations to be tailored to the farm's specific management practices.

On the other hand, developing and maintaining an in-house "mini-facility" for biologicals requires investment in infrastructure, personnel, biosecurity, and regulatory compliance—all of which compete for time and capital with core operations (planting, harvesting, and logistics).

In many cases—particularly for large corporate groups or lean operations—it makes more sense to outsource a significant portion of biological solutions, focusing management energy instead on carefully selecting partners, rigorously testing products in the field, and integrating these inputs into a holistic management system.

A mature decision often combines both approaches: internalizing less complex solutions (such as multiplying "robust" microorganisms linked to the farm's own waste streams) while purchasing more sophisticated biologicals—or those critical to operations or requiring quality control standards that are difficult to replicate internally—from third-party suppliers.

6.4. Governance and decision-making elements

How to align the technical team, the board, and investors: Large-scale adoption of bio-inputs impacts the budget, operational risk, and the business's long-term narrative; therefore, it cannot be managed solely at the "farm level" or just at the "board level."

Good governance begins with clarity regarding decision-making roles: the technical team designs and executes trials, the board sets risk limits and return targets, and investors or shareholders understand how this aligns with long-term strategy and issues such as ESG, carbon, and reputation.

In practice, this means making bio-inputs a recurring agenda item for technical and financial committees, establishing explicit criteria for moving from pilot to scale (or abandonment), and combining agronomic and economic indicators into simple dashboards that can be interpreted by both an agronomist and a financial advisor.

When this alignment exists, decisions are no longer driven by "fads" or commercial pressure but instead follow an agreed-upon roadmap of testing, learning, and scaling.

Transparency, data, and continuous learning: without reasonably consistent data, bio-inputs become just another layer of complexity added to an already complex system.

On large farms, this often manifests as duplicated fertilization, poorly calibrated applications, or hasty conclusions—such as "it didn't work" or "it's a miracle cure"—that lack a solid foundation.

Building transparency means recording—simply yet rigorously—what was applied, where, when, and under what soil and weather conditions, and then cross-referencing this information with productivity results, costs, and soil indicators.

Such data serves purposes beyond merely "looking back"; it acts as the raw material for a cycle of continuous learning, where errors are documented and turned into lessons, and future decisions become less reliant on individual memory.

In groups comprising multiple farms, internal transparency among units—even when it exposes shortcomings—is a key factor that accelerates system adjustments and lowers the cost of learning.

7. Conclusions

This report was driven by the central objective of analyzing the role of bio-inputs in large-scale systems, identifying where they generate real value. Throughout the investigation—which combined a literature review, international trips, and dialogues with producers, researchers, and industry representatives—it became clear that the discussion must be grounded in three layers of evidence: what is already robust, what is promising, and what remains unknown. This logic is applied below to each of the specific objectives.

Objective 1 – Map the adoption and the agronomic and economic results reported by large-scale producers.

Robust: Large-scale producers in countries such as the US, Brazil, and Australia are adopting bio-inputs **pragmatically and to address specific issues**—for example, inoculants for biological nitrogen fixation in soybeans or mycorrhizae for phosphorus efficiency in sandy soils. Economic returns are more consistent when the input resolves a high-cost production bottleneck.
Promising: Expansion into new crops (cotton, sugarcane, pastures) and the use of **synergistic combinations** (e.g., microbial consortia plus organic matter) show potential for increasing stability and resilience, though they still require validation at a commercial scale.
Unknown: How to reliably predict **response variability** across heterogeneous plots within a single farm, and the true medium-term economic impact of widely replacing synthetic inputs with biological ones.

Objective 2 – Identify the contextual factors that distinguish success from failure.

Robust: **Soil conditions (texture, organic matter, pH)** and climate are primary determinants. Systems with an already balanced management foundation—such as established no-till farming and crop rotation—respond better to the addition of bio-inputs.

Promising: The use of **advanced diagnostic tools** (sensors, soil microbiological analyses) to map variability and guide applications is evolving rapidly and can enhance decision-making precision.

Still unknown: how to **prioritize** these factors in day-to-day **operational decisions**—specifically, which indicator (e.g., enzymatic activity, microbial diversity) is the most practical and predictive for large-scale managers to make the right call at the right time.

Objective 3 – Assess the shift within the inputs and consultancy industry toward integrated management approaches.

Robust: Leading global companies and top-tier consultancies no longer sell "standalone products" but rather **technical packages** combining biologicals, fertilizers, genetics, and

monitoring. The long-term partnership model (as opposed to season-by-season sales) is a clear differentiator in successful cases.

Promising: **Integration with digital platforms** (Precision Agriculture, IoT, AI) for dynamic recommendations and the provision of support services for on-farm biofactories are trends that could accelerate adoption.

Unknown: Whether these more complex business models **are economically viable at scale** for the majority of companies in the sector, and how to balance the necessary technical sophistication with the simplicity required by producers.

Objective 4 – Discuss opportunities and risks regarding large-scale adoption in Brazil.

Robust: Brazil possesses **unique comparative advantages** for bio-inputs: a tropical climate that fosters microbial activity, extensive acreage under no-till farming, and a dynamic, innovative domestic industry. The potential to reduce costs associated with imported fertilizers serves as a powerful economic driver.

Promising: Recent **regulations governing on-farm production** (Law No. 15.070/2024) establish a legal framework that could boost producer autonomy, provided it is accompanied by quality protocols.

Unknown: The **aggregate large-scale impact** on the productivity and profitability of key commodities remains to be seen, as does how operational risks—such as logistics, quality control, and inconsistency—will play out when hundreds of thousands of hectares are transitioned to more biologically-based systems.

Objective 5 – Propose practical recommendations for the various stakeholders in the value chain.

Robust: Evidence shows that **any successful large-scale adoption requires intentional system design** ("design, not default"), starting with pilot areas (5–10%), and continuous, data-driven learning.

Promising: There is scope for **hybrid models** that combine the purchase of industrial inputs with on-farm production of less complex items, optimizing costs and autonomy.

Unknown: How to **translate these recommendations into public policies and financial instruments** that effectively reduce transition and error costs for producers without creating market distortions.

Final Summary

The use of bio-inputs in large-scale agriculture is not an overnight revolution, but rather a **gradual technical evolution**. What is currently robust fits into a well-defined toolkit: inoculants for legumes, mycorrhizae for phosphorus-poor soils, and biostimulants for specific stress factors. What is promising—such as applied soil microbiology, on-farm

bio-factories, and circular systems—is still under development, contingent upon context, management design, and ongoing validation. And the scope of what remains unknown is vast, particularly regarding economic predictability and operational scalability under real-world field conditions.

Positioning bio-inputs in this light—neither a magic bullet nor a passing fad—is perhaps this report's key contribution. For the large-scale producer, the takeaway is one **of informed pragmatism**: start with clearly defined problems, test rigorously, scale judiciously, and never lose sight of the fact that the true bio-input is the system as a whole.

Figure 24 summarizes the findings and conclusions regarding bio-inputs in large-scale agriculture.

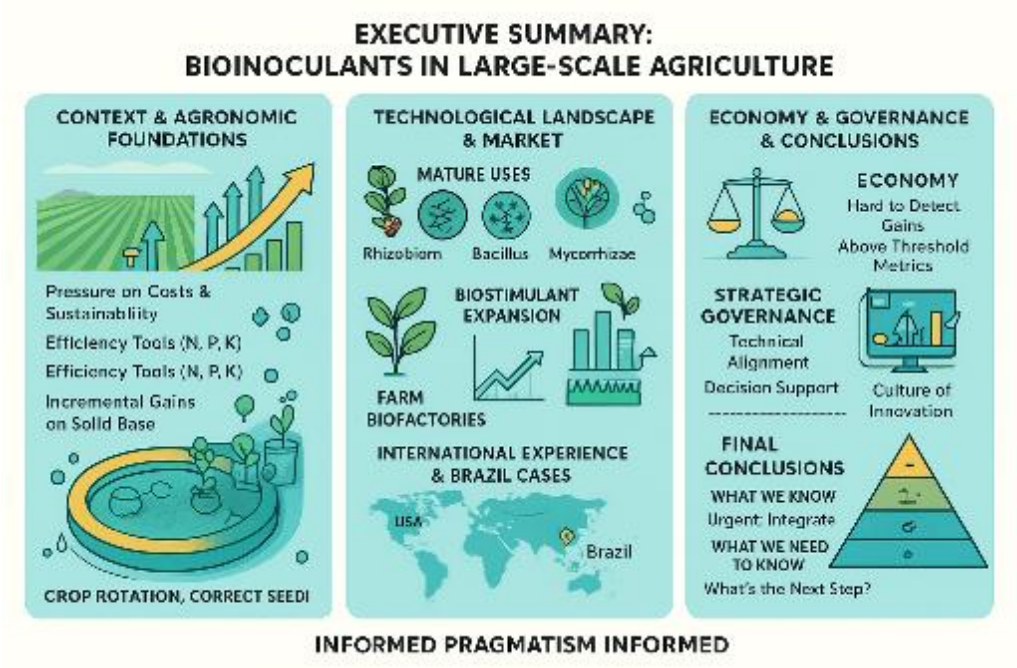

Figure 24. Illustration of the summary and conclusions regarding bio-inputs in large-scale agriculture.

8. Recommendations

8.1. Recommendations for large-scale producers

For large-scale producers, the key message is: treat bio-inputs as an integral part of the system design, not merely as a “nice-to-have” add-on to the chemical input model. Recommendations typically include starting small with clear hypotheses (identifying exactly where gains are expected), testing using a reasonably robust design, combining bio-inputs with adjustments to fertility, genetics, and soil management, and establishing an internal process to review results each season. In settings where on-farm biological production makes sense, a gradual approach to increasing complexity and scale is advised—always contingent upon the ability to ensure quality and traceability.

8.2. Recommendations for the inputs and services industry

For the industry, the report highlights the need to move beyond the "standalone product" mindset and focus instead on technical packages, protocols, and services that acknowledge the operational realities of large-scale farms. It recommends investing in data generated under commercial conditions—rather than relying solely on showcase trials—being transparent about product performance limits, and building long-term partnership models with producers and consultants, as opposed to relying on short, campaign-based sales cycles. There is also scope for developing hybrid solutions that combine product offerings with support for on-farm programs, rather than viewing the latter merely as competitors

8.3. Recommendations for research, public policy, and funders

For the research community, policymakers, and funders, recommendations converge on supporting medium-term systems-level studies that integrate soil, plant, climate, economics, and operational risk—moving away from fragmented, short-cycle trials. Policies and credit lines can be designed to lower the costs of transition (and of potential errors) associated with large-scale bio-input programs by making support contingent upon adherence to minimum standards for measurement and transparency. Funders entering the carbon and ESG space have an opportunity to explicitly value systems that employ microbiology and biostimulation judiciously, provided this is backed by verifiable metrics rather than mere narratives

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9. Appendices

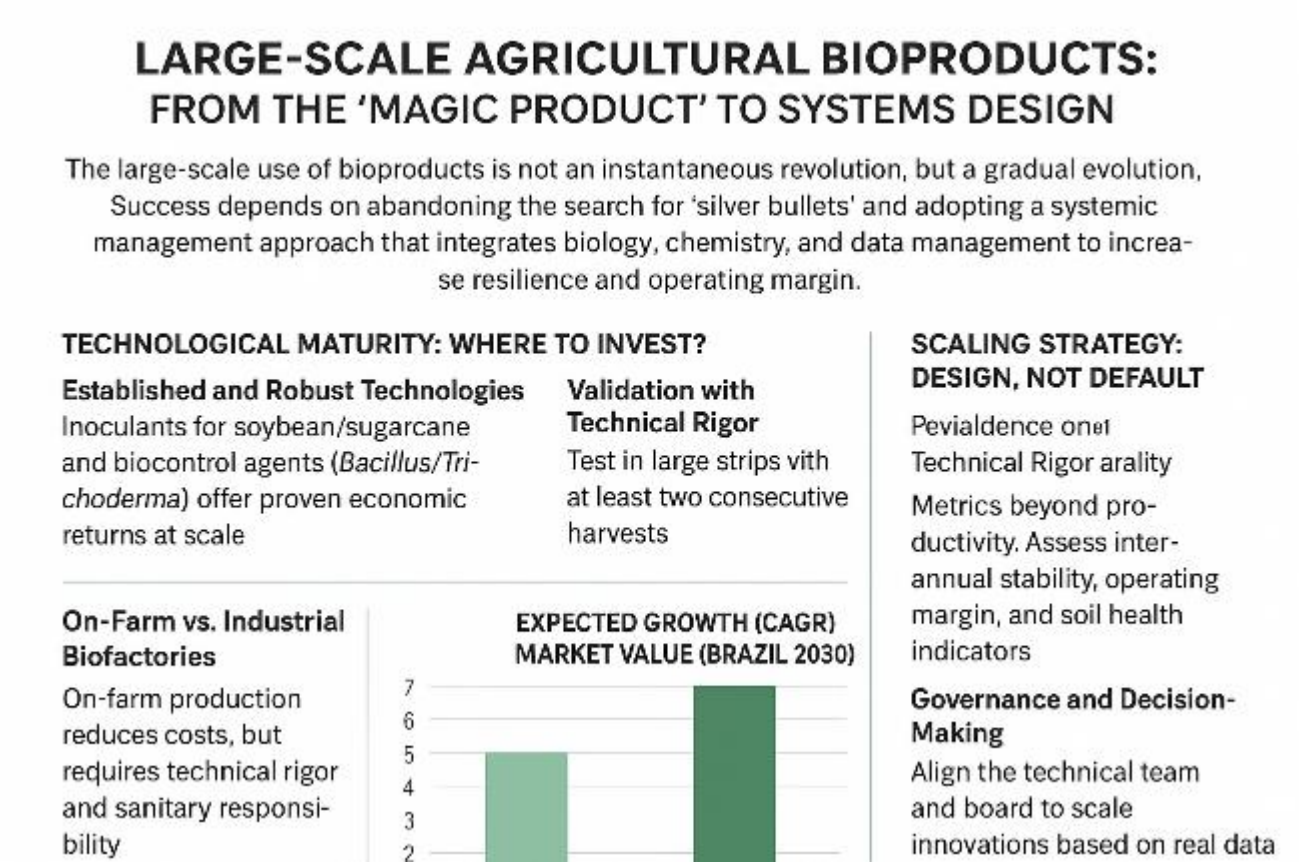

Figure 25. Mind Map of Bio-inputs in Large-Scale Agriculture: From "Magic Product" to System Design

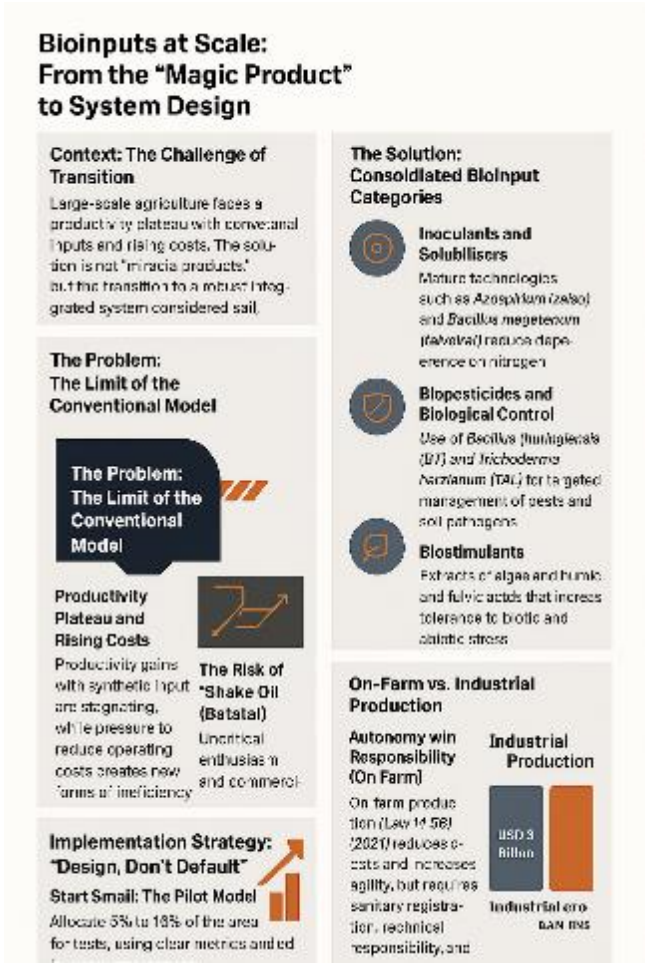

Figure 26. Mind Map of Bio-inputs in Large-Scale Agriculture: From "Magic Product" to System Design