



Comparative Assessment of Biofungicide Formulations: Strategies Towards Stable Biocontrol Products

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Abstract: The growing demand for sustainable disease management in agriculture has driven continuous development in biofungicide formulation. Despite advances in microbial discovery and screening, the formulation stage remains a bottleneck for commercialization due to limited shelf life, low field efficacy, and scalability. This review critically examines the performance, suitability, and scalability of biofungicide formulations, encompassing conventional (dry and liquid) and alternative forms (cell-free supernatants, microbial metabolites, and encapsulated systems). Dry formulations provide stability and ease of handling, while liquid formulations enable rapid microbial deployment but require protective additives. Alternative approaches, including the use of purified metabolites and encapsulated microbes, address issues of microbial viability and delivery but face challenges in formulation standardization and large-scale production. This paper also highlights formulation improvement strategies that revolve in the use of sugars as co-solutes in encapsulated formulations and the use of spore-based agents to enhance field survival and efficacy. Future research should focus on linking formulation design with microbial physiology and ecological performance to develop scalable, stable, and high-performing biofungicides.

Keywords: Biocontrol; biofungicides; formulation; stability; efficacy

1. Introduction

Improving agricultural productivity has become a critical priority in response to increasing global food demand and the need to ensure food security. One of the major constraints in crop production is the prevalence of phytopathogens, which are responsible for an estimated 20% to 40% loss in global yield annually [1, 2]. These plant disease causing phytopathogens include *Erwinia amylovora*, the causative agent of fire blight in apples and pears [3], *Colletotrichum gloeosporioides*, which causes anthracnose in mangoes [4], and *Lasiodiplodia theobromae*, responsible for stem-end rot in several tropical fruit crops [5].

Conventional control strategies rely heavily on agrochemicals, which, despite their effectiveness, pose significant environmental and health risks. These include contamination of soil and water systems, disruption of ecological balance, the emergence of resistant pathogen strains, and health-related concerns due to their ability to disrupt normal cell cycle regulation in humans [6-10].

Such concerns have accelerated the development of sustainable alternatives, particularly biological fungicides or biofungicides, which utilize either beneficial microorganisms or their bioactive metabolites to suppress phytopathogens in the field. Beneficial microorganisms effectively inhibit these fungal pathogens through two main mechanisms: antibiosis and competitive exclusion [11-15]. These mechanisms include induced systemic resistance (ISR) in host plants, siderophore production that limits pathogen access to essential nutrients such as iron, and the secretion of lytic enzymes that degrade fungal cell walls. Their consistent use can bring long-term disease suppression in the field, promotion of plant and root growth through nutrient solubilization, and compatibility with other sustainable practices, such as the use of biofertilizers [16, 17].

Despite their potential, the practical application of biofungicides remains limited by inconsistent field performance, short shelf life, and challenges in maintaining microbial viability during storage and application [18]. These limitations are not solely due to the biological agent itself, but are strongly influenced by formulation design, which governs stability, delivery efficiency, and interaction with environmental conditions. As a result, formulation has emerged as a critical bottleneck in the development and commercialization of biofungicide products.

To address these challenges, various formulation strategies have been developed, including conventional approaches such as liquid and dry formulations, as well as alternative strategies involving purified microbial metabolites, cell-free supernatants, and encapsulated systems. Each formulation type presents distinct advantages and limitations depending on the intended application, target pathogen, and environmental conditions. However, existing literature largely focuses on describing the different types and processes involved in biofungicide formulation [19-21], the composition and function of additives used [22, 23], mechanisms of biocontrol and a framework for development [24], or identification of key components in biofungicide development [25], with limited emphasis on systematic comparison across key performance criteria.

This review aims to provide a comparative assessment of biofungicide formulation strategies based on four critical parameters. First, stability, which refers to the shelf life and resistance to environmental stress. Second is efficacy, which is defined as the consistency and strength of biocontrol performance. Third is its scalability, which considers the feasibility of large-scale production. Lastly, the field applicability encompasses the delivery efficiency and compatibility of the biofungicide with current agricultural practices. By applying this framework, the review evaluates both conventional and emerging formulation approaches, identifies key trade-offs, and highlights areas requiring further research. Ultimately, this work seeks to bridge the gap between microbial potential and practical application by linking formulation design with performance outcomes, thereby contributing to the development of stable, scalable, and high-performing biofungicide products.

2. Formulation Types

Biofungicide field performance is inherently tied to formulation design, which dictates the product's physicochemical stability, delivery efficiency, and interaction with the environment. This design encompasses both the primary physical state of the product and the strategic incorporation of functional additives. These additives, such as surfactants, UV protectants, and anti-freezing agents, are essential for mitigating environmental stressors and optimizing application parameters in the field [25-27].

A robust formulation consists of three fundamental components: (1) the active ingredient (AI), which may include viable microbial antagonists (cells or spores) or their bioactive metabolites (purified compounds or cell-free supernatants); (2) the carrier, which facilitates the transport of the active ingredient to the target site; and (3) additives, which stabilize the system and maintain viability during storage [28]. In this context, the "additives" serve as an umbrella term for various functional subsets; specifically, co-solutes are additives used to improve microbial survival through osmotic or thermal regulation, while nutrient carriers are subsets that provide immediate metabolic support to the microbes during field establishment.

Biofungicide form can be categorized through a dual-axis matrix, as summarized in Figure 1 [29]. This approach distinguishes formulations based on their active-ingredient type (viable microbes vs non-

viable metabolites) and their physical form (liquid vs solid/dry). Within this framework, encapsulation and capsule suspensions serve as bridging technologies; they act as sophisticated delivery systems that stabilize both microbes and metabolites in either liquid or solid forms to enhance persistence and controlled release [30-33].

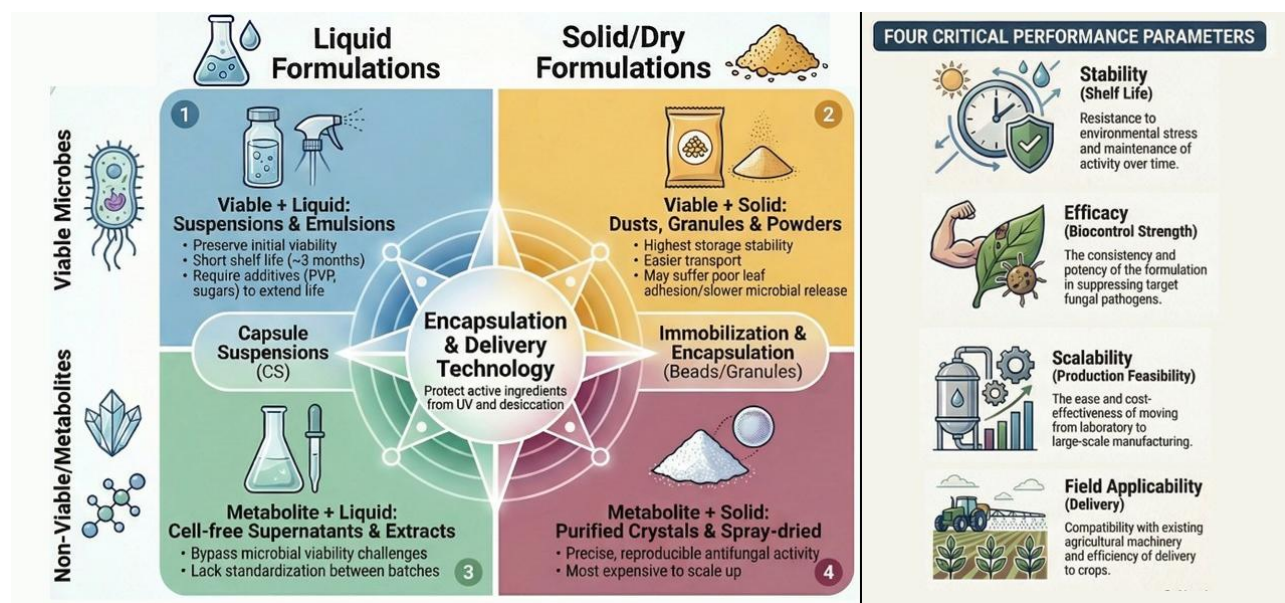


Figure 1. Overview of biofungicide formulation strategies, application modes, and performance considerations

2.1 Active Ingredient Selection: Viable Cells vs Non-Viable Metabolites

The first axis considers that the type of AI is the primary determinant of a product's biological mechanism and long-term reliability.

2.1.1 Viable Cells

The selection of the AI is a fundamental design decision in biofungicide formulation, as it directly influences stability, efficacy, and performance consistency. Broadly, biofungicide formulations utilize either viable microbial cells or non-viable bioactive metabolites.

Formulations based on viable cells rely on the microorganisms' ability to colonize the target environment, compete for nutrients and space while providing sustained biocontrol activity through the continuous production of lytic enzymes, biosurfactants, and siderophores, as well as the induction of systemic resistance (ISR) in host plants [34].

The advantage of this approach is demonstrated in the semi-commercial postharvest trials, where *Bacillus velezensis* TS3B-45 bacterial suspensions managed to control anthracnose in mango fruits [35]. However, the reliance on living systems introduces significant performance variability, as microbial survival and activity are strictly governed by their shelf life and high sensitivity to physicochemical stressors such as fluctuating temperatures, UV exposure, and moisture levels [36,37]. Consequently, maintaining viability during storage and after application remains a primary bottleneck for cell-based formulations, often necessitating the use of specialized protective additives or nutrient supplements to ensure long-term stability [38, 39].

2.1.2 Non-Viable Metabolites

Alternatively, non-viable microbial metabolites, which are bioactive compounds secreted during the fermentation process. To bypass the persistent challenge of preserving microbial viability during storage and application, these agents are employed either as purified molecules or cell-free supernatants (CFS). While this approach eliminates the viability bottleneck, it introduces new challenges regarding field persistence and production costs.

a. Purified Microbial Metabolites

Purified microbial metabolites have demonstrated potent antifungal activity through defined modes of action. Lipopeptides from *Bacillus* spp., such as iturin, surfactin, and fengycin, disrupt fungal membranes and inhibit spore germination [40-43]. These compounds have confirmed efficacy against various phytopathogens, including *Venturia inaequalis* (apple scab) [44], *Alternaria linariae* (early blight) [45], and *Fusarium oxysporum* f. sp. *iridacearum* (wilting and root rot) [46]. Similar results are achieved with purified lytic enzymes, specifically, such as β -1,3-glucanase, chitinase, and protease, which specifically degrade fungal structural components [13,47,48].

However, a critical limitation of purified metabolites is that fungal pathogens are not passive targets; some pathogens are capable of deploying counter-strategies such as chitin deacetylation, glucan masking, or the production of chitin-binding proteins to shield their cell walls from enzymatic access [49, 50]. Furthermore, fungal sensitivity to lipopeptides is heavily dictated by physicochemical determinants in the cell wall, such as ergosterol levels [51]. This indicates that reliance on a single purified metabolite may limit the spectrum of efficacy across diverse phytopathogens.

From a commercialization perspective, the long-term reliability of purified metabolites is undermined by high scalability hurdles. Production is often cost-prohibitive because active compounds accumulate in low quantities during standard fermentation. For example, optimization of iturin A from *B. subtilis* ZK-H2 yields only 0.85 g/L over 60 hours [52]. While higher yields of 6.8 g/L are achievable, they require specialized biofilm reactors, which increase the complexity and capital expenditure of large-scale production, often making purified forms less economically feasible than whole-cell formulations [53, 54].

b. Cell-free Supernatants

An alternative to purified microbial metabolites is the use of cell-free supernatants (CFS), obtained through centrifugation or filtration to remove microbial cells while retaining the extracellular metabolites. CFS is a strategically attractive biocontrol platform because it bypasses the viability bottleneck and leverages the synergistic cocktail of bioactive compounds secreted during growth, which is often harder for pathogens to resist than a single purified metabolite [55]. For example, 5% CFS from *B. subtilis* BS-1 inhibited *Botryosphaeria dothidea* (kiwi rot) by inducing oxidative damage and hyphal rupture [56]. Similarly, a 1% CFS from *Paenibacillus polymyxa* YF, *B. velezensis* BQ, and *B. amyloliquefaciens* HT significantly suppressed *F. oxysporum* [57].

However, a critical assessment reveals that CFS faces unique scalability and standardization hurdles [58,59]. A primary constraint is the requirement for low-temperature storage to maintain the structural integrity and biological activity of bioactive compounds; such as cold-chain requirements significantly increase commercialization costs and complicate large-scale logistics. While CFS offers a more practical and cost-effective production route than purified metabolites, it lacks the precision and reproducibility of purified molecules due to inherent variability in metabolite diversity and abundance across different fermentation batches [60]. Furthermore, compared with microbial cell-based formulations, CFS provides rapid initial antifungal action but lacks the field persistence afforded by living antagonists, which can colonize the host and continuously secrete bioactive compounds. Consequently, the efficacy of CFS is highly susceptible to environmental degradation from UV exposure and wash-off, often necessitating frequent re-application to maintain suppressive levels. This underscores a fundamental limitation; while CFS eliminates the challenges of maintaining microbial viability, its long-term reliability in the field requires integration into encapsulation systems to provide a physicochemical shield against environmental degradation.

Between purified microbial metabolite and CFS use, there is a trade-off between precision and practicality, as presented in Table 1. Purified metabolites provide precise and reproducible antifungal activity but are constrained by low yields and the high costs of scaling up. In contrast, CFS is easier to produce and scale, yet its application is hindered by variability in metabolite composition and difficulties in standardizing dosage across different phytopathogens. This duality underscores a fundamental limitation of metabolite-based biofungicides, as their long-term reliability often depends on the presence of viable microbes to ensure consistent activity.

Table 1. Microbial Metabolites Formulation [20, 59-61]

Property	Purified Microbial Metabolite	Cell-free Supernatant
Efficacy	Defined mode of action with reproducible antifungal activity. However, pathogen adaptability can limit effectiveness.	Rapid antifungal action due to the synergistic effects between metabolites. However, the optimal concentration to achieve the needed effects is highly variable.
Persistence in the Field	No to limited persistence in the field; requires doses due to metabolite degradation.	Also lacks viable microbes, but the metabolite concoction may prolong functional activity. Still subject to metabolite degradation.
Scalability	Expensive for large-scale production due to low yields per liter.	More scalable since only cell removal is required, but it suffers from a cold-chain requirement.
Applicability	Stable and easy to dose precisely; best suited for targeted, high-value applications.	Simple preparation and direct application; difficult to standardize dosage and frequency.

2.2 Physical States and Delivery Platforms

While the selection of the active ingredient defines the biological mechanism of the biofungicide, the physical state and delivery platform determine how that ingredient is protected, transported, and deployed in the field. This second axis of formulation design categorizes products into liquid or dry systems, each presenting distinct trade-offs between immediate bioactivity, storage stability, and economic scalability.

a. Liquid Formulations

Liquid formulations, also referred to as flowable or aqueous suspensions, consist of biomass suspended in water, oil, or emulsions [62]. Liquid systems represent a primary physical form of delivery that can accommodate both viable cells and non-viable metabolites. These formulations enable direct delivery of the active ingredient without exposure to dehydration or thermal stress during the process, thereby preserving high initial microbial viability and metabolic activity [63, 64]. Their biocontrol performance depends on the type and concentration of the active ingredient, stability, spray volume, water dilution, and droplet size, all of which influence the biofungicide's retention, coverage, and overall efficacy in the field [65, 66].

However, beyond the challenges of microbial viability, liquid formulations are inherently prone to gas build-up, especially if the microbe is active and is present at high concentration. While some reported that there is no clumping and sedimentation of biomass, it is still important to observe the formulation's physical properties [67]. Other properties to consider are the influence of storage temperature and the effect of the formulation's variable pH, as it can affect their pre or post-microbial application [68].

From a production standpoint, liquid formulations require the manipulation of high volumes of liquid with minimal protection from contamination [28]. Coupled with strict temperature requirements, this raises inconvenience for practical use, as having a short commercial life significantly increases the cost of storage [39]. Overall, liquid formulations provide clear advantages in terms of delivery efficiency and immediate bioactivity, particularly for foliar applications. However, these benefits are counterbalanced by challenges in maintaining long-term stability and consistent performance during storage. Compared to solid formulations, liquid systems prioritize ease of application and rapid efficacy but are limited by shorter shelf life, highlighting a fundamental trade-off between field performance and storage stability.

b. Dry Formulations

Dried formulations, on the other hand, involve combining a biologically active ingredient with a solid carrier to ensure delivery to the target site on the crop. A wide range of carriers has been explored in the literature, including charcoal, coal-bentonite mixture, talc, lignite, soybean meal, composts, corn meal, polyacrylamide gel, alginate, and perlite [69]. This makes them a more feasible alternative to liquid formulations, as they are reported to have low production costs and are easy to store and transport [28].

Several forms of dry formulations are commercially recognized, such as dust, granules, wettable powders, and water-soluble packets [65, 70]. These types differ in their physical properties and mode of application but share the advantages of relative stability in storage and ease of bulk transport, as summarized in Table 2.

Table 2. Evaluation of Dry Bioformulations [65, 70, 71]

Dry Formulation Type	Description	Advantages	Disadvantages
Dusts	Finely ground mineral powder (e.g., talc, clay) carrying an active ingredient.	Simple, low-cost, and easy to apply.	Low adhesion to target surfaces; inhalation and abrasion hazards.
Granules	Larger and heavier particles (100 to 1000 microns) with active and inert carriers.	Easy handling; reduced dust hazard; slow release	Limited foliar coverage
Wettable powders	Finely ground powders mixed with dispersants and surfactants.	Long storage stability; good miscibility with water, which allows foliar use.	Prone to clumping; inhalation risks; requires mixing with additives.
Water-dispersible granules	Compressed particles disintegrate in water to form a suspension.	Dust-free; uniform spray distribution	Requires constant agitation and specialized mixing equipment.
Water-soluble packet	Pre-measured doses in soluble film packets.	Safe handling; accurate dosing; reduces farmer exposure.	Higher production cost; limited adoption in resource-poor settings.

Regardless of the specific delivery format, solid-based formulations provide a protective and nutritive platform that enhances microbial survival compared to simple liquid suspensions [72]. However, when evaluated collectively, these types illustrate a distinct trade-off between scalability, stability, and field applicability. The simple options, such as dusts and granules, are highly scalable and inexpensive to produce; yet, their poor foliar adhesion and slow microbial release make them more suitable for soil-borne pathogens than foliar diseases. Conversely, advanced systems like water-dispersible granules (WDG) and soluble packets address critical needs for dosing accuracy and foliar delivery. However, these benefits are countered by higher production costs and physical requirements, such as the constant need for agitation to prevent sedimentation, which may limit their adoption outside of high-value cropping systems. These differences underscore that the success of a dry formulation depends not only on preserving microbial viability but on the physicochemical alignment of product design with the target pathogens and the economic realities of diverse farming systems.

2.3 The Encapsulation Bridge: Advanced Delivery Systems

Encapsulation serves as a technically sophisticated bridge between liquid and dry platforms, utilizing polymeric substances to immobilize and protect active ingredients (both the viable cells and metabolites) from environmental stressors. This can be achieved via encapsulation and capsule suspension formulation.

a. Encapsulation and Immobilization

Encapsulation serves as a technically sophisticated bridge between liquid and dry platforms, utilizing polymeric substances to immobilize and protect active ingredients (both viable cells and metabolites) from environmental stressors [54,72]. By using materials such as pectin-starch blends [73] or alginate-gelatin matrices [74], these systems create a physicochemical shield against various stressors, such as desiccation, UV radiation, and temperature fluctuations, while enabling the controlled release of the antagonist in the field [21,72]. This mechanism directly addresses the “viability bottleneck” identified in

liquid suspensions by maintaining high microbial fitness under fluctuating field conditions. Furthermore, the co-encapsulation of *B. velezensis* VRU1 in an alginate-gelatin matrix supplemented with nanoparticles significantly enhanced the inhibition of *Rhizoctonia solani* in beans [74]. These additive-enriched systems highlight the potential of encapsulation not only to protect the microbe but also to provide a localized, nutrient-rich microenvironment that promotes initial establishment in the host.

The commercial scalability of encapsulation is heavily dictated by the processing technique used, which ranges from extrusion-casting to fluidized-bed and spray drying [75]. A critical trade-off exists between microbial fitness and production efficiency. For example, *B. amyloliquefaciens* CPA-8 encapsulated via fluidized-bed spray drying demonstrated greater stability and shelf life than freeze-drying, yet the thermal and osmotic stresses of the drying process often necessitate the use of protective additives [76]. Protective additives such as skimmed milk and MgSO_4 have been shown to stabilize *B. subtilis* CPA-8 during spray drying to minimize heat and dehydration stress [77].

b. Capsule Suspensions

Capsule suspensions (CS) represent a technically sophisticated liquid delivery platform that bridges the field applicability of liquid sprays with the superior stability of encapsulated systems. In this format, the active ingredient is sequestered within microscopic polymeric shells suspended in an aqueous medium, creating a physicochemical shield against environmental stressors such as UV radiation and desiccation [78].

The primary advantage of CS is its ability to prolong field persistence through the controlled release of the antagonist to the target area. For instance, microcapsules of *B. megaterium* in calcium alginate beads have been shown to maintain high viability and colonization ability following foliar application, performing at levels comparable to non-encapsulated cells while gaining protection from the polymeric matrix [79]. The type of biopolymers used in the microencapsulation can be reinforced with other types of biopolymers, such as nanocellulose and chitosan [80]. This can lead to potential improvement in the physical characteristics of the microencapsulated material and an increase in antagonism properties due to the presence of chitosan.

Despite these performance benefits, the transition of CS from laboratory success to large-scale commercialization faces significant scalability and production costs hurdles. The complexity of the encapsulation process and the requirement for post-encapsulation stabilization remain primary bottlenecks. Consequently, while CS offers a promising high-stability and high efficacy solution for sustainable disease management, its adoption is currently most feasible for high-value cropping systems where economic returns justify the increased formulation costs.

To summarize the fundamental trade-offs inherent in the delivery platforms discussed, Table 3 provides a comparative synthesis based on the four performance criteria established in this review. This overview highlights how selecting an appropriate format requires balancing the physicochemical stability of the product with the economic and practical realities of diverse farming systems.

3. Formulation Improvement Strategies

Despite progress in developing various biofungicide formulations, field-level inconsistency remains a key barrier to adoption. Recent studies offer various strategies to improve current formulation types. This is either done using dormant or stress-tolerant propagules or by integration of multi-purpose additives to enhance field performance.

3.1 Use of Dormant or Stress-Tolerant Propagules

To address the viability issue in biofungicide particularly, its short shelf life of liquid suspensions and the metabolic exhaustion of vegetative cells, formulation design can shift toward the use of dormant or stress-tolerant propagules. While the active ingredient in a bioformulation can exist in a vegetative state, dormant spores offer superior physicochemical resilience against desiccation, temperature fluctuations, and UV radiation that typically limit the commercial viability of microbial products [29, 81, 82].

The transition from vegetative cells to spore-based agents provides a unique opportunity for mechanistic redundancy in the field. Unlike isolated metabolites, viable spores that successfully germinate and colonize the target area offer a sustained biocontrol effect through continuous antibiosis, competitive

exclusion, and the induction of systemic resistance (ISR). Biofungicides that use spore-forming bacteria, particularly from the *Bacillus* genus, are widely recognized for their strong antifungal capacity against pathogens such as *Phytophthora capsici* [16], various *Colletotrichum* spp. [83], and *Botrytis cinerea* [84].

Table 3. Comparative Synthesis of Major Biofungicide Formulation Platforms

Formulation Platform	Stability (Shelf Life)	Scalability and Cost	Field Efficacy	Practical Application
Liquid Suspensions	Prone to gas build-up; generally short shelf life	Straightforward to prepare; low production cost, but high logistic/cold-chain costs	Enables rapid microbial deployment and excellent foliar coverage.	Foliar protection requires immediate colonization and bioactivity.
Dry Formulations	Solid carriers provide a protective platform, easy to transport and store.	Simple dusts are cheap; advanced WDGs have higher technical complexity.	Dependent on moisture for activation, simple forms have poor foliar adhesion.	Soil-borne pathogens or large-scale broadcast applications.
Microbial Metabolites	Bypass viability bottlenecks but sensitive to UV and environmental degradation.	Purified forms are cost-prohibitive due to low fermentation yields.	Provides immediate antifungal action via defined modes of action.	High-value, targeted use or post-harvest disease management.
Encapsulation	Physicochemical shield protects cells/metabolites from UV and desiccation.	High technical complexity and carrier costs are primary bottlenecks.	Controlled release mechanisms prolong field persistence.	High-value cropping systems where long-term protection justifies cost.

a. Upstream Customization of Spore Properties

The sporulation process itself serves as a critical upstream determinant of formulation performance, where the physical properties of the “living” active ingredient are engineered during fermentation. As illustrated in Figure 2, process conditions such as pH and temperature during sporulation directly dictate the resulting spore surface hydrophobicity, adhesion, and UV resistance [85-87]. This can significantly dictate how the agent can adhere to the waxy cuticle of a leaf following foliar application and its survival on the surface of the leaves. Despite the potential for this physiological engineering, there is still a significant lack of empirical data linking specific upstream process conditions to downstream field germination or colonization behavior. This represents an underexplored frontier in biofungicide.

b. Scalability and Reduced Additive Dependency

The primary commercial advantage of spore-based formulations lies in their scalability and potential for process-based customization. In industrial settings, sporulation can be strategically induced at the end of vegetative growth, allowing for efficient scale-up in conventional fermenters before triggering the maturation of these durable units.

By optimizing the microbial physiology during production to yield robust, application-fit spores, developers can minimize the dependency on stabilizing additives, such as specialized co-solutes or UV protectants that are otherwise required to maintain the shelf life of sensitive vegetative cells [38,88]. Integrating spore physiology control into the production design thus offers a path toward consistent, stable, and high-performing biofungicide products that are better suited for the economic reality of large-scale agriculture.

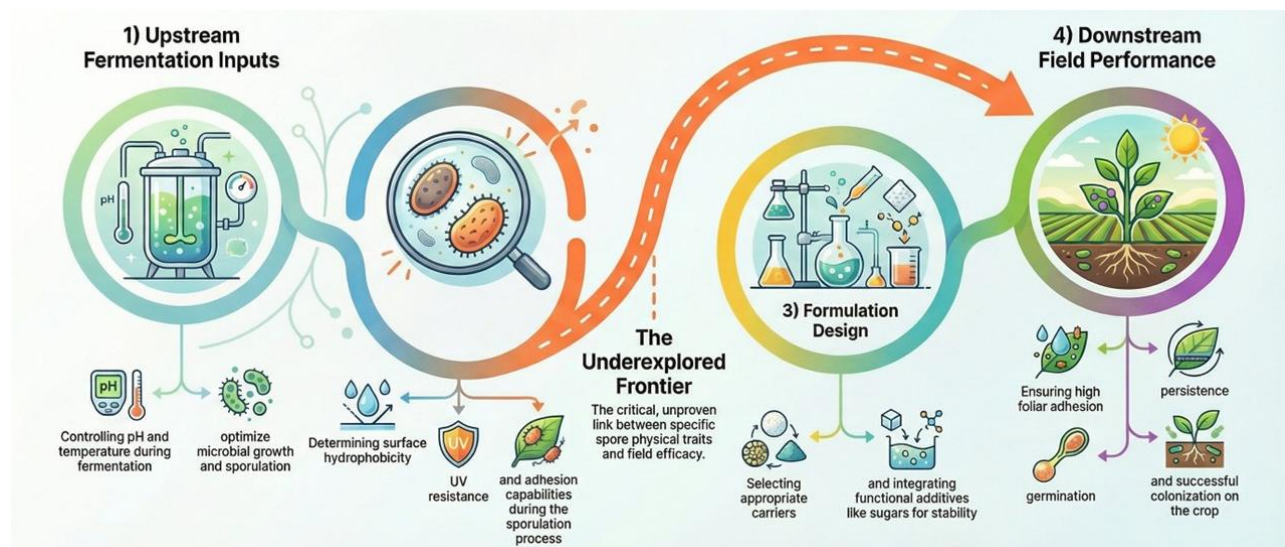


Figure 2. Conceptual framework illustrating how fermentation and sporulation conditions influence spore properties relevant to biofungicide formulation.

3.2 Sugars as co-solutes in encapsulation

To overcome the environmental stress tolerance and inconsistent field performance noted in liquid and dry platforms, recent strategies emphasize the integration of multifunctional additives that serve structural, protective, and nutritional roles. In encapsulation matrices, such as pectin or alginate, incorporating sugars as co-solutes, a functional subset of additives, that can significantly enhance gel firmness [89]. Furthermore, utilizing sugar-rich agro-industrial by-products like sugarcane molasses offers a highly scalable and low-cost substitute that improves the mechanical properties of gels such as pectin while simultaneously enriching the nutritional environment for encapsulated microbes [90]. This leads to a reduction in the concentrations of biopolymers and cross-linking for encapsulation [91].

Similar multifunctionality is observed with protein-based additives like skimmed milk, which can also act as both cryoprotectants and nutrient carriers during the dehydration and storage of agents like *B. subtilis* CPA-8 [76, 77]. These compounds form protective physicochemical shields around microbial cells, mitigating the desiccation and thermal shocks associated with production and application. While these additives promote rapid recovery upon rehydration, limited studies have linked gel entrapment with sugar nutrients to actual antagonistic effects in the field. This presents a vital research priority to determine how these integrated systems can optimize microbial survival and shelf life while maintaining the cost-effectiveness required for commercial adoption.

4. Conclusion

The formulation is the critical bridge that translates laboratory-scale microbial discovery into practical, field-level performance by determining the product's stability, delivery efficiency, and biocontrol efficacy. This review has demonstrated that each formulation platform presents inherent trade-offs. While liquid suspensions offer a rapid microbial deployment and ease of use, they suffer from a significant stability bottleneck and short shelf life. Conversely, dry formulations provide superior storage stability, yet advanced forms like water-dispersible granules often require specialized equipment that may limit adoption among resource-poor growers.

The most promising strategies for the next generation of biofungicides involve the integration of microbial physiology with formulation chemistry to overcome these limitations. Specifically, future work should prioritize the process-level customization of spore-based agents by utilizing upstream fermentation parameters to tune the resulting spores for enhanced physicochemical resilience and foliar adhesion. Alternatively, the rational use of multifunctional additives, such as sugars as co-solutes, can create protective matrices that enhance both the mechanical stability of encapsulation systems and the nutritional fitness of

the microbial antagonist. Lastly, there is the pilot-scale validation of these high-performing platforms (e.g., capsule suspensions) to ensure they remain cost-effective and scalable for commercial production.

Ultimately, achieving a “field-ready” biofungicide requires a holistic design approach that aligns product characteristics with the economic realities of farming systems. By shifting the focus from simple descriptive formulations to engineered systems that leverage the inherent durability of dormant propagules and the protective capacity of additive-enriched matrices, the industry can overcome the current commercialization bottlenecks and provide long-term, sustainable disease management solutions.

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