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Editorial note

From laboratory efficacy to field performance: closing the translation gap in botanical and microbial biopesticides

De la eficacia en laboratorio al desempeño en campo: cerrando la brecha de transferencia de los biopesticidas botánicos y microbianos

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ABSTRACT

Botanical and microbial biopesticides are promising components of sustainable pest management, yet their laboratory efficacy often fails to translate into consistent field performance. This Perspective argues that the central bottleneck is not the discovery of biologically active agents alone, but rather the preservation and delivery of biological activity under variable agricultural conditions. Ultraviolet radiation, temperature, desiccation, rainfall, volatilization, and oxidation can reduce effective exposure, while formulation, storage, and application constraints further limit performance. Recent advances in microencapsulation, nanocarriers, controlled release, and foliar-targeted delivery offer opportunities to protect active ingredients and improve persistence. However, technological sophistication must be balanced against field efficacy, scalability, environmental safety, regulatory feasibility, and cost. In this note, we propose that next-generation biopesticides be developed as integrated delivery systems that consider the active agent, formulation, application technology, crop, target organism, and environment simultaneously.

Keywords: biopesticides, botanical insecticides, encapsulation, field efficacy, formulation, microbial control

RESUMEN

Los biopesticidas de origen botánico y microbiano son componentes prometedores para el manejo sostenible de plagas; sin embargo, su eficacia en laboratorio a menudo no se refleja en un desempeño consistente en campo. En esta Perspectiva, sostenemos que el principal obstáculo no radica únicamente en el descubrimiento de agentes biológicamente activos, sino en la preservación y entrega efectiva de su actividad biológica bajo condiciones agrícolas variables. La radiación ultravioleta, la temperatura, la desecación, la lluvia, la volatilización y la oxidación pueden reducir la exposición efectiva, mientras que las limitaciones relacionadas con la formulación, el almacenamiento y la aplicación restringen aún más el desempeño. Los avances recientes en microencapsulación, nanovehículos, liberación controlada y sistemas de aplicación dirigidos al follaje ofrecen oportunidades para proteger los ingredientes activos y mejorar su persistencia. Sin embargo, la sofisticación tecnológica debe equilibrarse con la eficacia en campo, la escalabilidad, la seguridad ambiental, la viabilidad regulatoria y el costo. En esta nota, proponemos que los biopesticidas de próxima generación se desarrollen como sistemas integrados de suministro que consideren simultáneamente el agente activo, la formulación, la tecnología de aplicación, el cultivo, el organismo objetivo y el entorno.

Palabras clave: biopesticidas, control microbiano, eficacia en campo, encapsulación, formulación, insecticidas botánicos

Introduction

Biopesticides derived from microorganisms, plants, and other natural sources are increasingly important in the search for sustainable crop protection. They can complement or replace conventional pesticides within integrated pest management (IPM), while offering diverse modes of action and, for some products, favorable environmental profiles. Nevertheless, a persistent paradox remains: biological agents that produce strong mortality, inhibition, or disease suppression under controlled conditions frequently show lower or more variable efficacy in the field. Recent reviews identify environmental sensitivity, short shelf life, formulation limitations, production costs, regulatory constraints, and inadequate field validation among the major barriers to wider adoption of microbial biopesticides (Tadesse Mawcha *et al.*, 2025; Hamrouni *et al.*, 2025). The problem is therefore better framed as a translation gap than as a simple efficacy gap. Laboratory assays measure the intrinsic biological potential of an agent under standardized conditions, whereas field performance reflects the interaction between that potential and a heterogeneous environment. The critical question is consequently not only whether a biological agent is active, but whether its activity can be preserved and delivered at the target site for a sufficient period. This perspective considers the translation pathway from laboratory efficacy through environmental instability and formulation constraints to encapsulation, precision delivery, and next-generation biopesticides.

From laboratory efficacy to field performance

Laboratory bioassays are indispensable for screening plant extracts, essential oils, microbial strains, and metabolites. Controlled temperature, relative humidity, dose, and exposure time allow biological activity to be quantified with high precision. However, the conditions that facilitate discovery can also overestimate field performance. An insect exposed to a constant concentration of a botanical compound for 24–48 h is not equivalent to an insect encountering a declining residue on a leaf after exposure to sunlight, wind, and rainfall. Likewise, an entomopathogenic fungus that performs well at favorable humidity may show reduced infection after desiccation or ultraviolet exposure. Thus, laboratory efficacy should be interpreted as the first stage of product development rather than evidence of agricultural readiness.

Environmental instability. The agricultural environment can rapidly reduce the biologically effective dose. Ultraviolet radiation may degrade microbial propagules and light-sensitive molecules; high temperature can reduce microbial viability and accelerate chemical degradation; low humidity promotes desiccation; rainfall can remove residues from foliage; and wind can redistribute volatile compounds. For microbial agents, efficacy depends on survival long enough to reach or infect the target. For botanical products, volatility and oxidation may reduce residual activity even when they contribute to strong initial toxicity or fumigant effects. Recent reviews of microbial and nematode-based biopesticides emphasize environmental susceptibility and inadequate preservation as major constraints to field performance (Hamrouni *et al.*, 2025). This distinction is particularly important for botanical insecticides. Plant-derived compounds can possess strong insecticidal, repellent, antifeedant, or ovicidal properties, yet their rapid degradation and limited stability restrict field persistence. Kumar *et al.* (2025) identified rapid degradation, low stability, and limited field efficacy as major obstacles to the broader adoption of botanical insecticides. Consequently, increasing the nominal application rate is not necessarily the best solution. The relevant objective is to maximize the fraction of the applied dose that remains biologically active at the target site.

Formulation is part of efficacy. Formulation should be regarded as an integral component of the biological product rather than a final technological step. An active ingredient with excellent laboratory activity but poor environmental stability may be less useful than a moderately active agent incorporated into a formulation that maintains an effective concentration for longer. Conventional strategies include emulsions, suspension concentrates, oil dispersions, granules, wettable powders, seed coatings, and protective adjuvants. More advanced systems include microcapsules, nanoemulsions, polymeric carriers, and controlled-release formulations. For microbial products, formulation can protect viability during storage and after application. For botanical products, it can improve dispersibility, adhesion, photostability, and controlled release. A systematic review of micro- and nanocarriers found that natural polymers such as chitosan and alginate, together with synthetic polymers and inorganic materials, have been investigated extensively for encapsulating biological plant protection agents (Pinto *et al.*, 2022). The key conceptual shift is therefore from maximizing the amount of active ingredient applied to maximizing the amount of active ingredient that reaches the target in an active form.

Encapsulation and intelligent delivery. Microencapsulation provides a direct bridge between laboratory activity and field persistence. Protective matrices can reduce exposure to environmental stress while allowing the active agent to be released at an appropriate rate. Chitosan, alginate, and related biopolymers are particularly attractive because of their film-forming and encapsulation properties. Saberi Riseh *et al.* (2022) highlighted micro- and nanoencapsulation as strategies for protecting plant biocontrol agents and improving their practical performance. The next step is to control not only protection but also release. Stimuli-responsive systems can potentially respond to moisture, pH, temperature, light, or biological signals, creating opportunities to synchronize pesticide availability with environmental or pest conditions. Functional nanocarriers can also improve foliar retention and deposition. Recent work on bioinspired pesticide nanocarriers has emphasized molecular adhesion, structural matching to leaf surfaces, environmentally triggered release, and integration with precision agriculture (Chen *et al.*, 2025). These developments are particularly relevant for hydrophobic botanical compounds and environmentally sensitive biological agents. Nevertheless, nanotechnology should not be treated as a universal solution. A formulation that performs exceptionally well in a laboratory but is expensive, difficult to manufacture, unstable during storage, or environmentally persistent may have little agronomic value. The appropriate benchmark is therefore not nano versus non-nano, but whether an advanced formulation improves field performance, safety, and economic efficiency relative to the best available formulation.

Field validation remains the missing link. The disproportionate emphasis on laboratory and greenhouse studies remains a major weakness in biopesticide development. A successful laboratory assay should initiate progressively more realistic testing: laboratory, semi-field, greenhouse, field, multi-location field, and, ultimately, commercial validation. Field studies should report environmental conditions alongside biological efficacy, including temperature, relative humidity, rainfall, radiation, persistence, residual activity, application timing, formulation characteristics, and crop development. Without these data, it is difficult to determine why efficacy changes between environments. This issue is likely to become more important under climate variability. Higher temperatures, drought, irregular rainfall, and other environmental changes may widen the translation gap if formulations and application systems are optimized only under narrow laboratory conditions. Microbial biopesticide research already emphasizes the need for improved preservation, formulation, and field validation (Tadesse Mawcha *et al.*, 2025; Hamrouni *et al.*, 2025). The same principle should be applied systematically to botanical products.

Toward next-generation biopesticides

The next generation of biopesticides should be conceived as integrated biological delivery systems rather than isolated active ingredients. Such systems may combine a standardized biological agent with a protective formulation, controlled release, precision application, and environmental monitoring. Natural-product chemistry can define and standardize active compounds; microbial ecology can characterize survival and interactions with resident communities; materials science can develop protective carriers; and precision agriculture can determine where and when products should be applied. This convergence creates a new research agenda. For botanical pesticides, development should progress from extract screening toward chemical standardization, stability characterization, and formulation engineering. For microbial pesticides, viability, ecological compatibility, storage stability, and environmental persistence should be considered from the beginning. For both groups, formulation and delivery should be developed alongside biological discovery rather than after it. Computational approaches and artificial intelligence may further accelerate formulation optimization by identifying interactions among active ingredients, carriers, crop surfaces, target organisms, and environmental conditions. The final criterion of success should be reliable performance per hectare. A next-generation biopesticide should maintain sufficient biological activity at the target, under realistic environmental conditions, at a competitive cost and with acceptable effects on non-target organisms. This perspective is consistent with the broader direction of Pest Management Science, which emphasizes biopesticides, formulation, delivery, field performance, environmental safety, and novel targeted technologies within integrated pest management.

Conclusion

The principal challenge for botanical and microbial biopesticides is increasingly the translation of biological potential into reliable agricultural performance. Environmental degradation, volatilization, ultraviolet radiation, temperature, desiccation, and wash-off can reduce effective exposure, while formulation and delivery constraints can further limit efficacy. Microencapsulation, nanocarriers, and controlled-release systems provide promising routes to protect active agents and improve delivery, but their benefits must be demonstrated under realistic field conditions and evaluated against scalability, economics, environmental safety, and regulatory feasibility. The research priority should therefore shift from simply discovering highly active biological agents toward engineering delivery systems capable of maintaining effective exposure in the field. The most successful next-generation biopesticide will not necessarily be the product with the lowest laboratory LC_{50} or highest inhibition rate; it will be the one that delivers the right biological activity, at the right concentration, to the right target, at the right time, under real agricultural conditions.

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