Biopesticides in Horticulture

Guidelines for commercial field trials, grower assessment and industry adoption

Summary from International Biopesticides Research Workshop, June 2025.
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1 Executive summary

Validating the efficacy of biopesticides is essential for ensuring their reliability in pest control, regulatory compliance, and safe integration into sustainable agriculture. The purpose of this document is to provide guidance on rigorous validation of biopesticides through credible field trials to ensure their efficacy, safety, regulatory compliance, and commercial viability in sustainable agriculture. The guidelines describe the key considerations for manufacturers and registrants as well as for growers wanting to evaluate novel biopesticide products. Adoption of biopesticides depends on well-designed, effective trials that fit existing farming systems, and this guidance document supports planning and running commercial trials alongside country-specific regulations and practices.

Successful validation requires trials that reflect real-world production conditions to generate robust and objective third-party data and assess both agronomic fit and economic viability of biopesticides. Effective commercial trial design considers commercial production variables, appropriate controls, and clear endpoints such as pest reduction, measurable yield improvement, input cost savings, labour efficiency, or crop safety. Proper documentation, including environmental and application parameters, product composition, and statistical analysis, supports transparency and regulatory approval. Additionally, food safety protocols, such as quality assurance, traceability, and regulatory adherence, must be strictly followed.

*Success for biopesticides is defined by demonstrable **consistent efficacy**, clear Return on Investment (**ROI**) for growers, environmental **compatibility**, and **ease of integration** into existing practices.*

Biopesticide trials under commercial field conditions are essential to assess performance amid variations in climate, soil, water quality, and integration with existing pesticide programmes. Commercial trials also highlight potential challenges in grower adoption and guide education and outreach efforts. Designing robust commercial trials requires clear research objectives, validated modes of action, standardised methods, and independent and appropriate data collection to ensure transparency and credibility. Trials must be designed to generate credible data on efficacy, economic return, and environmental compatibility while supporting regulatory compliance and grower confidence. Transparent and accurate data management supports regulatory approval, fosters industry trust, and enables meaningful comparisons across regions.

Ultimately, biopesticide adoption will result from overcoming the known challenges and providing region-specific and data-backed recommendations for effective application. Ensuring consistent efficacy is the biggest hurdle to grower adoption for biopesticides. Products with broad efficacy claims and inconclusive or inappropriately analysed data do more harm than good to the biopesticide industry. The Guidelines for commercial trials describe the integration of biopesticides into commercial farming operations; Grower support and outreach and clear trial summaries will support informed decision-making and collaboration among industry stakeholders. Finally, guidance for growers to support the assessment of biopesticide products as well as for industry to support the adoption of biopesticides are also provided.

By following standardised methods and effectively communicating results, commercial biopesticide trials can facilitate integration, enable informed decision-making, and drive responsible integration into sustainable agricultural systems. These guidelines provide a practical framework for growers and other stakeholders to collaborate effectively, overcome adoption barriers, and contribute to the long-term viability of biopesticides in commercial agriculture.

2 Contents

2. Purpose of the Guidelines

Biological products[1], including biopesticides are often presented as an ideal solution to address existing and anticipated gaps in plant health and pest management for agricultural production. Given the numerous and diverse biopesticide products entering the specialty agriculture or fresh produce scene, validation of biopesticide products is critical to ensure that growers are properly equipped with the tools to address new and ongoing challenges. Trial protocols that address the key challenges and growers' needs to appropriately assess the efficacy of biopesticide products can support better adoption and success for biopesticides in fresh produce crop production.

These guidelines, developed by industry and research experts, are intended to provide product registrants, growers, commodity groups, and other stakeholders facilitating the evaluation and adoption of biopesticides with scientifically sound and industry-focused direction, focused on effectiveness, sustainability, and economics. Drafted at the International Biopesticides Research Workshop, held in June 2025 at the University of California, Davis, much of this guidance is based on work previously developed by industry experts, cited in the reference section of this document.

Conducting commercial trials for biopesticides often involves greater complexity than trials evaluating classical pesticides (also called chemical, synthetic, or traditional pesticides). This document offers a framework for developing standardised biopesticide trials and assessments and aims to assist in informed decision-making. While the guidelines presented are broadly applicable, it is important to recognise that trial design will vary depending on the target pest and product functionality (e.g. bioinsecticide, biofungicide, or bioherbicide). The primary focus of these guidelines is on biopesticide products targeting pests (insects, pathogens, and weeds), with an emphasis on considerations relevant to research and data collection.

This international guidance document is intended to support the planning and execution of commercial biopesticide product trials and should be used alongside the regulatory requirements and agricultural practices specific to each country. International collaboration on the development, validation, and adoption of biological alternatives is essential to ensure consistent, science-based standards that support grower confidence and market access across borders. As growers around the world increasingly look to integrate biopesticides into their production practices, global coordination can help reduce assessment redundancy, streamline regulatory pathways, and accelerate the adoption of effective biopesticide products and practices. Validation and assessment protocols that reflect shared grower needs and environmental goals is critical ensuring success in addressing global pest management and plant health challenges.

Individual growers are often inundated with requests to test new and emerging products and determining the efficacy of these various products can be a challenge. This document contains suggested check points for growers to consider when assessing fit for trialing new products.

Finally, the document contains guidelines to assist the wider industry with increasing uptake and adoption of biopesticides. To achieve greater adoption and build industry-wide confidence with biopesticides as viable pest management solutions, industry alignment on best practices for biopesticide adoption is needed. Implementing the recommendations will enhance industry confidence, facilitate responsible adoption of biological products, and support sustainable agriculture practices in fresh produce crop production.

[1] Biological products, biologicals and biologics are broad terms that represent biopesticides and other tools for crop protection and production. Definitions are included in Appendix 1.

2.1. Specific considerations for horticulture and specialty crops

These guidelines have been developed primarily for assessment in horticulture, also called speciality crop systems, including fruit, nut and vegetable crops. Horticulture crops, and especially fresh produce, are grown in agricultural systems that are distinct from commodity row crops, also called broad acre or arable crops. Data on the performance, efficacy, and economics of biopesticide products are needed specifically for horticulture crops. Geography, seasonality, production systems, and many other factors differ across crop species, varieties and production regions so commercial trials in local areas are required to understand the varying effects on speciality crops.

3. Background

Global trends towards de-registration and reduced availability of classical pesticides (also called chemical, synthetic, or traditional pesticides), increased pesticide resistance due to the past over-reliance on specific modes of action (MOAs), increasing concerns for human and environmental health (e.g. to growers and consumers through persistence of residues), and new pest challenges requires more innovation, efficacy and adoption of biopesticides in agriculture. Biological products, including biopesticides (Figure 1), are often presented as the ideal solution to address existing and anticipated gaps in plant health and pest management for agricultural production.

Interest and investment in biological alternatives to traditional agricultural inputs has been growing rapidly across the globe. Currently valued at around USD $14.7 billion, the biological products market is predicted to grow to around USD $27.9 billion by 2028 (Markets and Markets 2025). However, navigating the complex landscape of emerging biological products (often referred to as biologicals) has been challenging for fresh produce growers. In 2023, Western Growers partnered with the Mixing Bowl Hub to map the agricultural biologicals landscape (The Mixing Bowl 2023). This overview identified 1,200 companies with products derived from naturally occurring micro- and macro-organisms, plant extracts, and other natural materials used to enhance crop production by acting as plant biostimulants, biofertilisers and biopesticides (Figure 1). An updated overview in 2024 (The Mixing Bowl 2024) identified 300 companies delivering biological crop protection products (biopesticides), targeting multiple pests including insects, mites, nematodes as well as plant diseases and weeds.

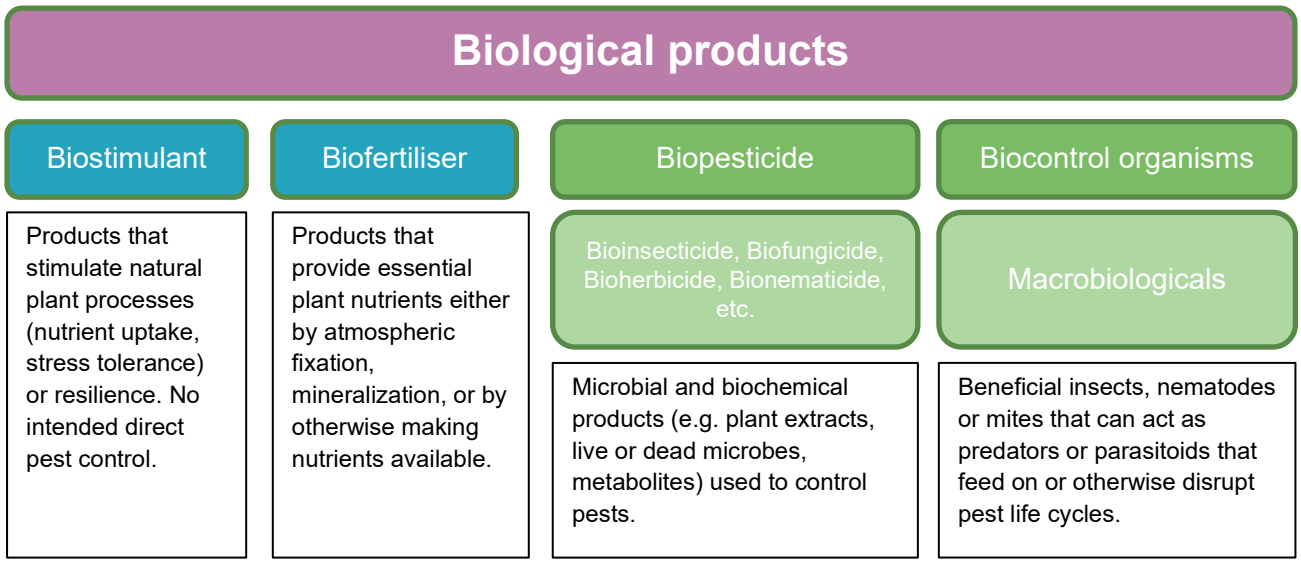

Figure 1: The Biologicals Landscape: Biostimulants, biofertilizers, biopesticides, and biocontrol organisms make up much of the Ag biologicals landscape. Definitions will differ by country and regulatory framework. Refer to Appendix 1 for further definition of these categories of biological products.

When compared to classical pesticides, biopesticides may not be directly comparable in terms of knockdown, residual control, and environmental requirements. Fundamental differences in biopesticide modes of action (MOA), target specificity, environmental behaviour, and performance dynamics provide opportunities for improved resistance management (e.g. rotating MOAs to reduce selection pressure and/or enhancing effectiveness of classical chemistries), economics, efficacy, innovation, sustainability credentials and environmental stewardship. Biopesticides may also better protect beneficial species needed to prevent secondary pest outbreaks, have reduced phytotoxic effects on crops, and work synergistically with other inputs and tools to extend application intervals. Because biopesticides are typically more sensitive to degradation than classical pesticides, they may also support residue management, allowing for shorter re-entry periods.

3.1 Biopesticide product development pipeline

While this document provides guidance mainly focused on commercial trials for biopesticide products, the entire biopesticide development pipeline - from discovery through to commercialisation and grower adoption - is critical to the overall success of biopesticides. While the development process is typically depicted as a linear pipeline (Figure 2), the process is often iterative and requires developers to revisit earlier stages to refine formulations, adjust application methods, or improve efficacy based on trial outcomes and emerging data. While the pipeline guides the development of effective, safe, and commercially viable biopesticides, it is not a strict or guaranteed path to success. More detailed information on each stage of the pipeline is provided in Appendix 2.

Different kinds and scales of efficacy assessments and field trials are needed throughout the biopesticide product development pipeline. Following discovery of a biopesticidal microorganism/bioactive, small-scale evaluation of its effectiveness is first evaluated under highly artificial laboratory conditions. If the candidate looks promising, it will then be evaluated in small scale greenhouse and pot trials under controlled conditions that begin to approximate field conditions. Larger scale controlled and replicated field trials will then be undertaken to evaluate the performance of the biopesticide under more realistic environmental and biotic conditions (variable weather, range of soil types, exposure to natural pest densities).These field trials will often be undertaken by researchers or developers at research farms and orchards, where conditions can be regulated, e.g. irrigation provided as required with sites selected to optimise the likelihood of detecting a treatment effect. Factors to consider when running these early field evaluations are addressed in Appendix 2. The next and crucial step is the evaluation of biopesticides under realistic commercial growing conditions, sometimes referred to as demonstration trials. Guidelines and recommendations around best practice for design and execution of commercial field trials are provided below in Section 4.

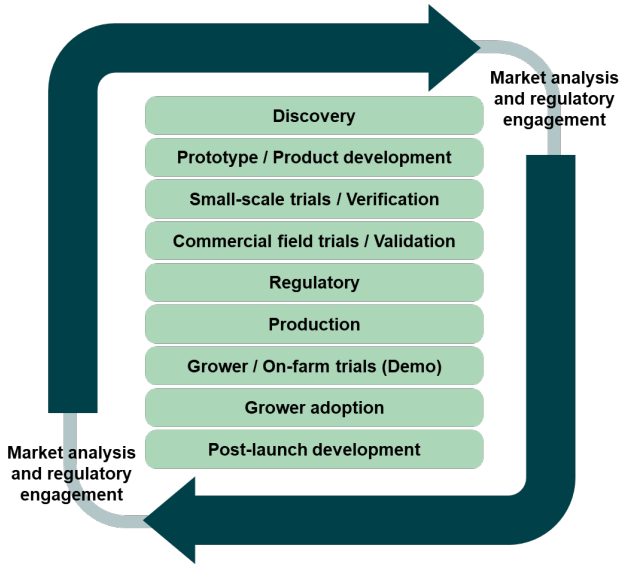

Figure 2: The biopesticide product development pipeline. The pipeline involves key stages such as discovery, validation registration and market acceptance.

4 Guidelines for commercial biopesticide trials

Biopesticide trials in commercial field conditions are critical to understanding the diversity of elements and factors that occur at the commercial scale. Considerations such as fit in current pesticide programmes, interactions and compatibility with commercial inputs, variations in climate and environment, and inherent factors such as soil and water quality, or crop rotation can provide insight into product performance variability and grower adaptation or education needs.

These guidelines for commercial trials are specific to biopesticides that are advanced in the registration process and offer solutions to challenges for pest control with fresh produce crops. With the understanding that much of the success of pest control will result from Integrated Pest Management (IPM) or Integrated Crop Management (ICP) and include on-farm practices and programmes that are not always product-based, it is critical therefore to understand and consider interactions of biopesticide products and best practices for successful pest control.

4.1 Framework for biopesticide trials

Designing trials for biopesticide products in horticulture and agriculture begins with clearly defining the research question and identifying the specific data required to answer it. Whether assessing efficacy, MOA, or integration into growing systems, a robust trial must be built around measurable outcomes. Biopesticide product trial design must account for environmental interactions, target specificity, and application timing.

To build broad-scale reputational trust there must be a transparent framework that biological products are required to pass through. This framework should include scientifically sound criteria such as a clearly defined and validated MOA, consistent efficacy across conditions, and safety for non-target organisms. Trials should be standardised where possible, with replication, appropriate controls, and rigorous data collection. Ideally, product validation should be conducted by an independent third party, and the resulting data should be publicly accessible to support informed decision-making and separate high-performing products from those with limited value. Such an approach not only strengthens scientific integrity but also fosters grower confidence and regulatory alignment.

4.1.1 Validation

Validating the efficacy of biopesticide products is crucial to ensuring effective of control pests and minimise harm to the environment, beneficial organisms, and human health, while protecting farmers from economic loss and the industry from poor category acceptance. Proper validation can reinforce the capabilities of biopesticides to provide reliable pest control for fresh produce crops, meet regulatory standards, and offer sustainable alternatives to classical pesticides. Providing growers with more and diverse pest control options can provide product alternatives and rotation options to reduce pesticide resistance development in pests and support long-term agricultural productivity and sustainability.

4.1.2 Data collection and management

Ensuring the transparent, accurate, and standardised data collection and management for biopesticide trials shared with the trial growers is essential. Additionally, the reliability and credibility of results directly impact regulatory approval, commercial adoption, and optimisation of efficacy on commercial farms. Alignment of data standards promotes meaningful comparisons across trials, facilitates data sharing and transparency, and supports evidence-based decision-making by growers, researchers, and regulators. Further, international collaborations can facilitate the identification of patterns in product performance, environmental interactions, and best-use practices, ultimately

contributing to the successful integration of biopesticides into effective pest management systems. More work is needed to address data sharing and transparency, particularly with trials with poor outcomes that may disincentivise data sharing from commercial operations.

Third-party objective data collection and reporting:

- Third party trials are often conducted by university or extension researchers, or by Contract Research Organisations (CROs)
- Data collection and reporting should include a detailed description of trial design including the number of plants per plot and subplot, management schedules, control treatments, statistical analysis, and an executive summary with key highlights.
- Reporting may include weather history and deviations throughout trial dates, soil type and basic properties, irrigation, other input applications (i.e. any crop inputs applied during production) and application timing to account for variations in temperature, humidity and UV.

4.1.3 Industry fit

Biopesticide products that are a good fit for the fresh produce industry are aligned with the specific crop, pest or disease management priorities of growers. This includes confirmed effectiveness across production practices that reflect real-world seasonality and agronomic conditions. Trials to validate biopesticide products must be designed to match commercial production variables, while objective third-party data collection and analysis, including weather, soil, irrigation, and statistical analysis, ensures unbiased results that support product registration and adoption. Biopesticide products that demonstrate a good industry fit include:

Justification and objectives:

- Verified need and economics within the crop/pest/issue priorities
- Established timeliness and accessibility to include appropriate variety and representative crop selection, cropping cycle, production practices, and seasonality
- Justified site selection to include typical soil types for growing region, pre-trial pest and disease scouting undertaken to verify presence of target pest
- For registration purposes, new pesticide product candidates are normally tested as stand-alone treatments against a chemical standard and untreated control. However, in commercial scale trials, it is important to assess the fit and efficacy of the new product within a management programme.

Variables to fit commercial crop production:

- Trial location, plant variety, and planting dates to coincide with commercial production of target crops
- Agronomic practices and pest control options to coincide with commercial production for target crops.

4.1.4 Alignment with Integrated Pest Management (IPM) or Crop Management (ICM)

Biopesticide products align with IPM, ICM or agroecological principles, particularly if the MOA offers targeted pest control to minimise harm to non-target organisms, humans, and the environment. Specific MOAs may reduce the risk of pest resistance and preserve beneficial species. Biopesticides may be applied as a preventive treatment or in combination with other IPM tactics, such as crop rotation, biological control, and habitat management, to maintain pest populations below damaging points.

4.2 Commercial trial implementation

4.2.1 Plot size, placement, and location

- Treated plots must be large enough to effectively observe the biological effects (e.g., disease severity or insect damage) being evaluated and minimise the influence of treatments on adjacent plots, and sampling must be adequate for commercial extrapolation.
- Area must allow for product application using commercial equipment and accurate yield measurement. Plot size should allow multiple data collection points (repeated measures over time) for product efficacy assessment during the trial, for example, weekly insect counts or disease severity assessments.
- Strip plots are commonly used to compare new products and product rotations side by side with the grower's current practice. Employ adequate buffer zones between each of the plots to prevent cross-contamination.
- Acceptable buffer zones will vary depending on the pest challenge or severity and crop. Consider target pest mobility relative to the mechanism of action of the product undergoing evaluation. Account for patterns of pest movement across fields and uneven distribution.
- Replicates for treatments, more is better wherever practicable.
- Pseudo-replicates may be used in lieu of true replication if true replication cannot be achieved, for example, due to space restraints; however, this must be noted in the field trial protocols' description. This can be achieved via random in-row sampling with Randomised Complete Block (RCB) design, anticipating patterns of non-uniformity within a field. Collect unbiased data by coding the treatments to prevent subconscious bias.
- Include adequate industry standard and untreated controls and controls for any adjuvants.
- Besides effect on pests, assess effect on plant growth and vigour as well as signs of phytotoxicity.
- Trialling product on multiple locations and crop species is highly recommended.

Trial design is critical to assessing the efficacy of biopesticides. Resources such as 'The Labcoat Guide to Crop Protection R&D: Books I–III' (Teicher 2019) may support decisions surrounding selecting the appropriate design elements.

Protocols should include the following data:

- Application method, rates per hectare/acre (by mass or volume of formulated product), re-treatment interval, Pre-Harvest Interval (PHI) and Re-Entry Interval (REI)
- Spray volume (gallons or litres per hectare/acre) and nozzle type
- Timing relative to crop development and/or pest status
- A list of suitable application equipment types including optimal target pressures and droplet sizes
- Environmental conditions for application (e.g. time of day, temperature, humidity, wind speed)
- Instructions on tank mixing (e.g. buffering pH)
- Additional guidance on water quality needs. Consider antimicrobial effects if using live microbes

- Verify compatibility with known chemistries used in commercial production or that interfere with the test compound or cause foaming. Consider antimicrobial effects if using live microbes
- Any suggested adjuvants (e.g. spreader stickers, emulsifiers) and optimal rates
- Tank mixes or treatment programmes rotating more than one product
- Preferred product maintenance (e.g. temperature, expiration date).

4.2.2 Product Information

- Required product information may be determined by relevant regulatory authorities
- Provide product label in accordance with existing data for crops /disease/issue to be evaluated
- Include product claims and correlating data to support.
- Describe MOA and define what the measured outcomes will be (e.g. incidence, severity, Area Under the Disease Progress Curve [AUDPC], yield, quality, marketable/unmarketable yield, vigour, mortality, growth, colour, brix, grade, firmness). If measuring yield, provide results in actual yield difference per hectare/acre and not percent yield increase from control. Include average or anticipated yield given seasonal fluctuations
- For insecticides, include the physiological pathway(s) affected, speed of action, and how exposure is achieved (e.g. direct contact, residual contact, ingestion)
- For fungicides, include the physiological pathway(s) affected, speed of action, and whether the compound works through contact or is systemic and whether the product application is preventative or curative
- Include peer-reviewed literature to support product or Active Ingredient (AI) efficacy
- Describe inert ingredients and potential impacts on crop growth if possible and provide any available information regarding negative effects to a crop and the circumstances that can contribute to negative effects
- Provide a standard error of the mean for all means presented (number in tables and using "whiskers" in bar charts)
- Statistical data analysis (means comparison) with appropriate level of experimental error.

4.2.3 Defining Success

Success for biopesticide product trials in agriculture typically involves understanding clear and measurable benefits, practical usability, and economic viability. An effective biopesticide should show not only acceptable pest or disease control, but also a positive impact on farm productivity, such as increased yield, reduced input costs, improved labour efficiency, or greater flexibility in crop rotations. For example, even if a product is not comparable to conventional treatments, such a product could still be useful in some contexts and in some combinations. Specifically, success would mean:

Effective disease or pest control:

- Repeatable and statistically significant reduction in disease incidence, severity, or pest populations compared to untreated or conventional treatments
- Consistent results across different environmental conditions and cropping cycles
- Measurable increases in yield, marketable crop quality, or improved uniformity

- Positive impacts on crop vigour, health, or resilience against abiotic stress factors such as drought or heat.

Economic viability:

- Clear return on investment (ROI) for growers, benefits outweigh the cost of the biopesticide product material or product application
- Productivity metrics should be reported in clear, farm-relevant terms (e.g. yield per area unit, input cost per area unit, labour hours saved, or number of spray passes reduced), and a summary of Year 1 ROI for the grower should be included whenever possible
- Competitive economics when compared or integrated with chemical alternatives or existing practices, or added value of resistance management, and organic integration.
- Ease of integration into existing agricultural practices:
    - Compatibility with current farming equipment, procedures, and agronomic schedules
    - Practical application methods (e.g. ease of use, timing flexibility, stability, storage requirements).
- Environmental and regulatory benefits
    - Reduction in chemical inputs or improvement in environmental outcomes (e.g. lower pesticide residue, improved soil health, reduced runoff)
    - Alignment with regulatory requirements or marketplace certifications (e.g. organic or sustainable farming practices).

Replicability and consistency:

- Clearly define conditions (e.g. soil type, moisture, crop, and timing) where consistent benefits can be expected
- Develop targeted usage recommendations rather than generalised promises of efficacy
- Provide thorough and transparent communication about expected variability and methods for optimising results
- Clear documentation and transparent methods facilitating adoption by growers and acceptance by industry stakeholders.

4.2.4 Describe target assessment endpoint of grower trials

- Determine efficacy against the pest (% control), compare to local industry standard or a local pesticide rotation programme and to the negative control
- Determine quantity of marketable yield and compare with control treatments in the same trial
- Show ROI, economic analysis that demonstrates the efficacy providing enough benefit to offset costs and provide economic benefit
- Determine non-target costs/benefits; for example, low/no harmful effects on beneficial insects or impact on non-target beneficial
- Confirm any challenges with product storage, food safety, shelf life, quality of product over time
- Confirm crop safety and lack of phytotoxic effects
- Confirm compatibility and ease-of-use with commercial application equipment.

4.2.5 Additional considerations

- Describe the ‘control’ treatment that is used as comparison, with ideally, both an untreated control and the grower’s current practice as comparison treatments. Noting that growers may prefer to avoid untreated control plots.
- Many growers leverage more than one standalone pesticide product to control insects and diseases. Biopesticides can be incorporated into the grower’s standard IPM rotation or tested as a standalone product against the standard grower programme.
- Costs associated with crop destruct and grower compensation for lost harvest or yield loss due to product use should be made clear before beginning the trials process.

4.3 Reporting

Reporting results using a standard template to report research results is crucial to align international efforts to trial biopesticide products to ensure consistency, transparency, and comparability across studies conducted in different regions and by various stakeholders. Standardisation allows researchers, regulators, and industry partners to evaluate efficacy, safety, and environmental impact using harmonised data, facilitating regulatory approvals, reducing duplication of effort, and accelerating the development and adoption of biopesticides globally. Growers and other key stakeholders can easily navigate results. A standard template supports data sharing and strengthens collaborative research aimed at sustainable pest management solutions (see Appendix 3 for Report Template).

5 Guidelines for grower biopesticide assessment

Growers are often inundated with product trial requests, and navigating the efficacy of these various products can be a challenge. The following guidance includes suggested check points for growers to assess fit for trialing new products.

5.1 Guidelines for biopesticide assessment

5.1.1 Product fit

- The product has undergone rigorous proof of concept and small field trials for the specific pest/issue/crop/location that it will be applied towards.
- The product has been researched in relevant geographies with consistent results.
- The product has shelf life or storage needs that can be accommodated on-farm.
- Questions: Does it require refrigeration? Can the container be opened and stored without risk of contamination? In what form will the product arrive at the farm?
- The product can be applied with the specific water quality that is available on the farm.
- Questions: Can the product be mixed with chlorinated water or withstand Cl residue in conveyance materials? Can the product tolerate low or high pH water? Are there specific temperature requirements?
- The product can be applied with standard farming equipment or equipment is available at reasonable cost. The type of application equipment will usually determine the minimum plot size in a grower trial.

5.1.2 Data vs. Product Claims

When choosing a pest management product, it's important to critically evaluate the data provided in sales materials. Compare trial data with the product claims. Understanding how the data were collected and analysed can help you make informed decisions. Learn more about summary statistics in this article and this video.

- Check for a description of the mechanism of action
- Look at the variability of data (averages and the range) in the results
- Check for information on replication and sample size, feasibility on farm
- Understand the experimental design and environmental conditions
- Does the product have clear, independently validated data showing a positive impact on farm productivity (yield, cost, labour, or risk reduction) in addition to pest control?

5.1.3 Product Availability

- Is enough product available from the manufacturer to cover a full season or full application cycle?

- Is the product manufactured locally, and if not, will there be concerns with product availability based on transport logistics or international trade?

5.1.4 Product and Trial Costs

When evaluating biopesticides in commercial trials, it is crucial to consider the full scope of associated costs to ensure accurate budgeting, feasibility, and effective management, as outlined in Figure 3. Additionally there may be food safety considerations (described in Appendix 4) Useful questions may include:

- What is the expected product cost per hectare/acre through the local distributor?
- Is the manufacturer providing the test material for a grower trial free of charge?
- Who is responsible for trial applications, assessments and harvest? And who can or will have access to that data?
- Are the results going to be published or confidential?
- Does the manufacturer or distributor compensate for possible crop/yield losses/damage in the trial area?
- Does the manufacturer/distributor request unrestricted access to the trial site?
- Does the product require research authorization or crop destruct?

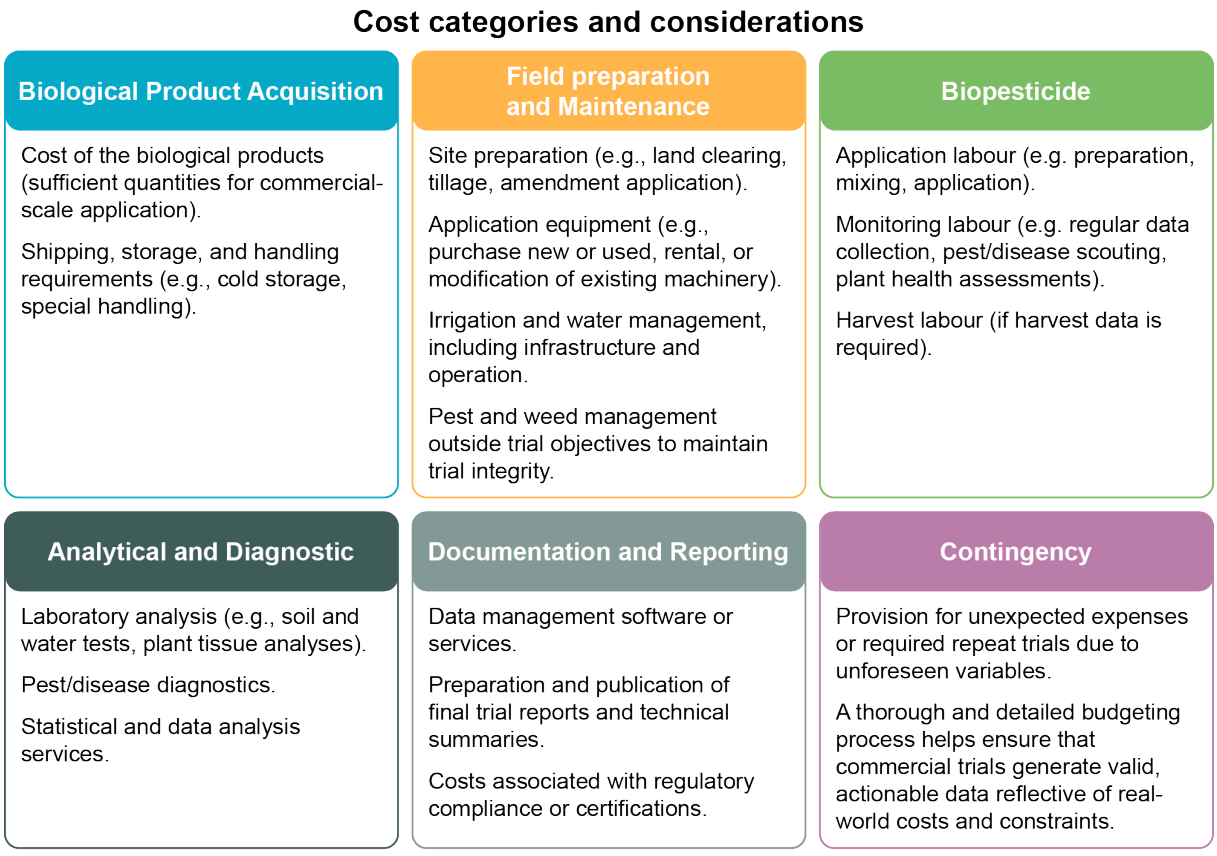

Figure 3: Typical cost categories and considerations.

6 Guidelines for industry biopesticide adoption

To advance successful adoption and industry-wide confidence in biopesticides as viable pest management solutions, it is critical for the industry to align on best practices for biopesticide adoption. Implementing these recommendations will help enhance industry confidence, facilitate responsible adoption of biological products.

6.1 Guidelines for Biopesticide Adoption

6.1.1 Clearly define optimal conditions for use

- Establish and communicate detailed conditions (e.g. soil types, moisture levels, temperatures, and crop growth stages) under which biopesticides have consistently demonstrated efficacy
- Develop region-specific application recommendations to guide growers on effective product use tailored to local conditions.

6.1.2 Develop targeted usage recommendations

- Avoid generalised efficacy claims. Provide clear, data-backed recommendations outlining the expected range of effectiveness
- Offer specific guidance on integration into existing IPM programmes, including compatibility with other products and cultural practices.

6.1.3 Transparent communication and grower education

- Clearly document and openly communicate expected variability, emphasising realistic outcomes based on trial results
- Provide growers with educational resources (e.g. webinars, workshops, written materials) focused on optimising product performance and managing expectations
- Establish easy-to-understand summaries and key takeaways from field trials to facilitate informed decision-making.

6.1.4 Industry collaboration and continued validation

- Encourage collaboration among stakeholders (e.g. registrants, researchers, extension specialists, and growers) to continuously validate product efficacy across diverse commercial settings.
- Promote long-term studies to capture variability across multiple growing seasons and environments, thereby refining recommendations and enhancing product credibility.

6.2 Challenges in grower and industry adoption

6.2.1 Trial design and execution

- Trials may not be designed around the biopesticide’s specific mode of action
- Lack of replication, leading to uncertainty due to field variability
- Poor execution of trials (e.g. overspray, early harvest, lack of documentation)
- Inappropriate or missing controls, including positive controls

- Trials not accounting for environmental conditions or pest development stages
- Trials conducted at an inappropriate spatial scale for the pest or production system
- No clear intermediate measurements when results aren't immediately visible
- Trials comparing biopesticides directly to synthetics without considering biopesticide-specific effects
- No pre-sampling to ensure sufficient pest pressure
- Uneven pest or disease distribution across plots
- Trials pulled early or compromised (e.g. site sprayed or harvested prematurely)
- Inadequate measurement of contextual data (e.g. microclimate, soil health).

6.2.2 Biological and environmental factors

- Pest or disease not present or below a measurable threshold during the trial period
- Multiple or unexpected pest species complicating analysis
- High variability in weather and environmental conditions between seasons
- Uncontrolled variables like weeds affecting trial outcomes
- Not understanding pest biology or lifecycle (e.g. insect phenology)
- Not understanding the product's mechanism of action or how it reaches the target.

6.2.3 Operational and logistical issues

- Product application challenges (e.g. powder clogging equipment, needing unchlorinated water, tank mixing issues)
- Timing issues (e.g. product applied too late, poor site availability)
- Side effects like increased labour, soil compaction, or fuel use
- Misalignment between manufacturer-recommended protocols and grower logistics
- Poor training of researchers or trial personnel
- Difficulty accessing appropriate equipment or labour
- Not understanding capabilities or limitations of application technologies

6.2.4 Communication and knowledge gaps

- Poor communication between growers, researchers, and manufacturers
- Misunderstanding or lack of clarity about product requirements
- Lack of training in innovation or trial acceleration principles
- Manufacturer not sharing all necessary information for successful application
- Trials run by personnel unfamiliar with the mode of action or pest biology
- Lack of guidance on integrating products into existing grower systems

6.2.5 Data and analysis limitations

- Trial data not published, especially negative results
- Incomplete or improper data analysis to determine causes of failure
- Framing of the trial question too vaguely, resulting in missing critical data

- Absence of standardised data collection methods (e.g. lack of ISO standards)
- Failure to collect necessary performance metrics (e.g. soil health indicators)
- Uncertainty about whether results are transferable across seasons or regions.

6.2.6 Product stability and market confidence

- Products released before being fully validated or stable
- Changes to product formulation after initial marketing damage trust
- No indication of product "stability" or likelihood to change over time.

7 Appendix 1: Definitions

Term	Definition	Reference
Biological Products	Crop protection products derived from living organisms or natural substances. To manage pests, diseases, and weeds, often as part of Integrated Pest Management (IPM) programme. Active constituent (whether living or not) comprises of or is derived from a living or dead organism (e.g. plant, animal, virus, microorganism), with or without modification, but where some essential characteristics of the source material are retained in the product.	CropLife International Australian Pesticides & Veterinary Medicines Authority
Biopesticides	A subset of biologicals that includes microbial pesticides (e.g. *Bacillus thuringiensis*) or biochemical pesticides (e.g. plant extracts).	EPA NZ Australian Pesticides & Veterinary Medicines Authority
Biofungicides	Biological products that suppress fungal pathogens using beneficial microbes that inhibit or outcompete disease-causing fungi.	AIP Conference Proceedings
Biological control	A method to control pests using other organisms such as predators, parasites and pathogens, instead of pesticides.	Australian Pesticides & Veterinary Medicines Authority
Biological Control Agents	Living organisms such as insects, mites, fungi, or bacteria introduced to control specific pests or diseases. These agents are typically host-specific and environmentally safe.	EPA NZ
Beneficial Microorganisms	Microbes like bacteria or fungi that colonise plant surfaces or soil. Crop resilience, nutrient acquisition or protection against pests or diseases are notable functions.	BASF Global
Beneficial Insects and Mites	Predators or parasitoids (e.g. lady beetles, lacewings, parasitic wasps) that feed on pest insects such as aphids, caterpillars, and whiteflies. Predators that feed on plant pests. Pest management systems should monitor and encourage the presence of these insects as they reduce the reliance on, or need for, chemical insecticides.	Ecosystems United Australian Pesticides & Veterinary Medicines Authority
Biorational Pesticides	Selective pest control agents that are safe for non-target organisms and often compatible with biological controls due to their short residual activity. A pesticide based on bacteria, viruses, fungi or protozoa, including pest control agents, and chemical analogues of naturally occurring biochemicals (e.g. pheromones, insect growth regulators).	EPA NZ Australian Pesticides & Veterinary Medicines Authority
Biostimulants	Substances or microorganisms that stimulate natural plant processes to enhance nutrient uptake, stress tolerance, and crop quality. Do not directly control pests but may improve plant resilience.	Biostimulants beginners guide: introduction, impact and advantages - CABI BioProtection Portal
Biofertilizer	Living microorganisms (e.g. Rhizobium, Azotobacter, mycorrhizae) that enhance soil fertility by fixing nitrogen, solubilising phosphorus, or improving nutrient availability.	Biofertilizers Definition - Types of Biofertilizers and Its Benefits
Crop Destruct	Special handling in cases where un-registered pesticide used in the field in trial setting requires the crop or harvest to be destroyed and not used for human or animal consumption.	

8 Appendix 2: Biopesticide development pipeline

The biopesticide product development pipeline involves key stages such as discovery, validation registration and market acceptance. This biopesticide product development pipeline was developed in collaboration with international researchers focused on biopesticide development, assessment, and commercialisation. Biopesticide Adoption Guidelines outlined below encourage transparent communication about performance variability and integration into bespoke or existing IPM programmes.

8.1 Discovery

The initial discovery phase involves identifying and assessing promising new candidates to determine potential viability as biopesticides.

The focus is on understanding a pest/disease problem and how a new product could reduce it. This initial discovery stage includes targeted and untargeted new MOAs, innovations that aim to provide effective degrees of control.

Understanding markets and associated commercialisation pathways, particularly product deployment and integration into existing farming practices, should be considered from the outset. Therefore, to ensure the success of biopesticide product development, scientific discovery must be closely aligned with the practical challenges faced by growers. Researchers should assess whether the proposed solution addresses real agronomic needs, such as synthetic pesticide resistance management, or gaps in current pest or disease control options, and determine its feasibility within existing farming systems. This includes evaluating whether the product can be seamlessly integrated into growers' routines, equipment, and crop cycles without requiring major operational changes. Delivery mechanisms and context of use must be carefully considered, including system coverage, environmental limitations like temperature and humidity, and compatibility with irrigation or spray technologies. By grounding innovation in the realities of field conditions and grower priorities, researchers can develop biopesticide solutions that are not only scientifically sound but also practical, scalable, and widely adoptable.

8.1.1 Characteristics of discovery

Effective research into new biopesticide products begins with a thorough understanding of what control options exist along with their limitations, the specific pest or disease problem that needs a solution, its agricultural impact, and the broader scope of intervention. Researchers may also take an untargeted approach, allowing for open-ended exploration of novel biopesticide mechanisms. Identifying promising innovations from university laboratories, research institutions, and peer-reviewed scientific literature is essential to stay at the forefront of emerging technologies.

The nature of experimentation, i.e. in-vitro, versus in-vivo, must be carefully chosen based on the bio-agent's characteristics and intended application. Technical viability and scalability are critical checkpoints, ensuring that discoveries can transition from lab to field without compromising efficacy or cost-effectiveness. Additionally, delivery methods, system compatibility, and application limitations must be clarified early in the research process to avoid downstream barriers in formulation, deployment, or regulatory approval. Together, these considerations form the foundation for a robust and strategic research pathway toward impactful biopesticide solutions.

Identify Potential Solutions: *Research promising scientific discoveries from university labs (e.g. in-vitro versus in-vivo studies).*

Market Need*: Assess if the product meets grower needs and if it fits into existing farming practices.*

Feasibility and Delivery: *Evaluate how the product would be applied in specific systems, considering coverage and other limitations.*

Stakeholders: *Key players include start-up investors, researchers, growers, commodity groups, and university intellectual property (IP) offices.*

8.1.2 Guidelines for discovery

Consider the target market, market size (industry pull), existing competing product, local or global, IP issues, ROI, technical readiness, commercial readiness, replacement or integrates, awareness of likely future de-registrations, iterative. A decision tree may include:

1. Understand the challenge

- Conduct field surveys, consult agronomic data to identify pressing pest or disease issues
- Engage with growers, agronomists, and industry stakeholders to validate the real-world impact.

2. Define the problem and scope

- Narrow down the target organism(s), crop systems, and geographic relevance
- Refine the rationale for the target, i.e. resistance, market access, environmental safety, or efficacy
- Consider suitability of the target to a biopesticide solution e.g. large, robust mobile insects may be poor targets, soil borne diseases may be hard to contact.

3. Specify research direction

- Targeted Research: Develop hypotheses around specific biopesticide mechanisms or known biocontrol agents.
- Untargeted Research: Use high-throughput screening or metagenomic approaches to explore unknowns.

4. Identify promising innovations

- Review recent publications, patents, and conference proceedings.
- Collaborate with universities or research institutes to access novel strains, extracts, or technologies.

5. Choose experimental approach

- In-vitro: Ideal for early-stage screening, mechanistic studies, and controlled bioassays.
- In-vivo: Necessary for assessing proof-of-concept, real-world efficacy, host interactions, and environmental behaviour.

6. Evaluate technical and economic viability and scalability

- Assess stability, shelf life, and formulation compatibility.
- Run pilot-scale production tests and cost modelling to evaluate commercial feasibility.

7. Clarify delivery and application

- Consider compatibility with existing spray equipment, irrigation systems, or seed treatments.
- Identify limitations such as temperature sensitivity, UV degradation, or tank-mix restrictions.

8.2 Proof of Concept Trials

The small-scale trials and verification stage proves the product's proof of concept in a controlled environment before moving to larger, more extensive trials.

Small-scale trials play a critical role in the early development of biopesticide products. These trials offer a controlled environment to evaluate efficacy, mode of action, and crop safety before advancing to field-scale testing. They enable rapid screening of multiple formulations and application strategies, helping identify and refine the most promising biopesticide candidates. Potted trials are particularly valuable for detecting phytotoxicity and understanding plant-pest interactions, ensuring that products are both effective and safe for horticultural use. The data generated from these trials also supports regulatory submissions and informs commercial trials and feasibility, making them an essential step in the development pipeline.

8.2.1 Characteristics of proof-of-concept trials

Small-scale trials are a foundational component of biopesticide product development, requiring thoughtful planning and specialised infrastructure that can control environmental variables and biological interactions. These trials may focus on a single crop or system or explore broad applications for wider market appeal, under controlled conditions, noting broader assessment may occur (or re-occur) at later stages if a single target is identified.

Proof of concept trials primarily focus on efficacy and crop impacts, and the purpose of the trial should be clear. Efficacy should be evaluated both comparatively, against industry standards or products with the same/similar target pest or pathogens, and to understand standalone performance, dose rate and delivery. True replication is essential, including untreated controls and appropriate positive controls, to ensure statistical validity and meaningful interpretation. Trial duration must also reflect the nature of the biopesticide product, especially for short-term actives that require multiple treatments, so results can inform realistic grower trial planning and application schedules.

Proof of Concept: Conduct trials in labs, greenhouses, and growth chambers to verify the product's efficacy.

Data Collection: Use methods like sequencing and remote or automated phenotyping to gather data.

Efficacy Assessment: Compare the product's performance against existing treatments and industry standards (comparative vs. absolute efficacy) in a single cropping system or a broader application.

Stakeholders: Researchers, Investors, regulators, and extension organizations (e.g. University of California Agriculture and Natural Resources agricultural extension [UCANR],) are crucial.

8.2.2 Guidelines for proof-of-concept trials

1. Determine infrastructure or operational requirements and ensure access to appropriate facilities:

- Laboratory: For formulation, microbial culturing, and molecular analysis.
- Greenhouse/Growth Chamber: For controlled environment testing on whole plants.
- Microcosm Systems: Especially important for nematode trials and soil-based interactions.
- Incorporating remote or automated phenotyping can enhance data accuracy and throughput if these facilities are available.

2. Cropping or system selection:

- A single cropping system for targeted development or multiple crops to assess broader applicability and market potential.
- Consider if a crop or model system can provide an exemplar for proof of concept or provide a more suitable testing method.

3. Efficacy evaluation with consideration for:

- Comparative efficacy: Benchmark against industry standards or conventional products.
- Absolute efficacy: Measure standalone performance of the biopesticide product.

4. Experimental design

- Include fully replicated experimental designs to ensure statistical validation
- Untreated controls to establish baseline conditions.
- Positive controls (e.g., known effective treatments) for comparison.
- Delivery method reflects the biopesticides' MOA.

5. Trial duration and treatment should align with the bio pesticide product's MOA:

- For short-term actives, plan for multiple treatment applications.
- Ensure timing reflects realistic grower practices to support future field trial planning.

8.3 Field Validation Trials

The field validation trials phase tests the product under realistic growing conditions to validate its effectiveness and consistency.

8.3.1 Characteristics of field validation trials

Field validation trials for biopesticide products should be strategically designed to balance scientific rigor with practical relevance. Initial pilot-scale trials, i.e. a few tree replicates or small plots, allow for early performance insights under semi-controlled conditions. These could gradually expand regionally, incorporating replication across diverse growing environments to assess consistency and adaptability or incorporate full design, if implementable. Deployment on a small-scale in commercial

grower fields is essential to evaluate product behaviour under operational conditions, including standard farming schedules, management practices and environmental variability.

Trial design should avoid over-engineering solely for statistical replication. Instead, trials should prioritise realistic application strategies that reflect how growers will use the product while maintaining statistical rigour. Researchers must determine optimal timing and methods of application, identify differentiating factors compared to chemical controls or other biopesticides, and adjust protocols when ideal conditions are not feasible, documenting any justified deviations. Clear identification of key measurements is critical for product validation and regulatory submission, especially when translating lab or greenhouse rates to field-level efficacy. Where required, crop destruct or special handling protocols and experimental use permitting should be planned in advance to comply with regulatory standards prior to product approval.

> **Trial Design:** Begin with small-scale trials and then scale up with replications across different growing regions to ensure consistency.
>
> **Data and Application:** Place materials in grower fields and collect data that differentiates the product from competitors. This includes determining the best application timing and methods as well as economic data, including ROI.
>
> **Problem Solving:** Address the common difficulty of translating lab rates to field rates and decide on justified alterations when ideal conditions aren't possible.
>
> **Stakeholders:** This includes Contract Research Organizations (CROs), manufacturers, government-funded research (IR-4), universities, extension services, regulators, growers and representative industry bodies.

8.3.2 Guidelines for field validation trials

1. Determine trial objectives

- Clearly define the specific questions or hypotheses the trial aims to address e.g. How does the biopesticide product impact pest mortality? Does it improve crop yield under standard farming conditions? Does it deliver measurable improvements in farm productivity (e.g., yield, input cost reduction, labour savings) under standard farming conditions? How does it compare to current standard practices in terms of both pest control and overall farm profitability?

2. Define response variables by trial objective and scale

- Target pest or disease specific: Mortality, sublethal effects (e.g. fecundity, activity, lifespan),
- Crop specific: Damage levels, pest population dynamics, early yield indicators, final yield, quality metrics, economic return, pest suppression consistency, or carryover of inoculum between crops (e.g. spores in soil or plant residues).

3. Determination spatial scale based on:

- Spatial dynamics of the target organism
- Mode of action of the active ingredient
- Crop layout and canopy structure.
- Ability to measure ‘benefit’ from a grower perspective

4. Environmental and agronomic data (Metadata) collection to enable regional/global comparison

- Climate data (temperature, humidity, rainfall)
- Soil moisture, structure and type, this may include historical data that could influence current conditions
- Crop metadata: cultivar/variety, spacing, planting system (bed size, trellis design), crop age/size (for permanent crops).

5. Trial equipment and calibration

- Describe the equipment used for product application
- The calibration process and results to ensure accurate dosing, avoid equipment that cannot be reliably calibrated (e.g., backpack forced-air sprayers).
- Record application success e.g. coverage on abaxial and adaxial leaf surfaces, deposition at multiple canopy strata (minimum two, depending on crop height).

6. Timing and Growth Metrics

- Calculate timing based on crop and pest or disease physiology/life stage. This may include the use of growing degree days (GDD) to time application and measure crop and target development stages or based on expert scouting and life stage identification.

7. Data collection protocol

- Standardise data collection methods across trials, for interpretive results link data to the individual undertaking the collection.
- Collect response variable data based on selected pest or disease and target crop.
- Pest data should include:
    - Pest counts, damage assessments.
    - Disease incidence, severity, or description of pest populations.
    - Yield and loss, and other quality measurements meaningful to the grower.
    - Sublethal impact assessments.

8. Return on investment (ROI) evaluation to supports economic analysis:

- Input costs vs. yield gains.
- Reduction in chemical use.
- Labor and operational efficiency.

9. Defining Benefit Consistently

- Establish clear criteria for what constitutes a "benefit":
- Statistically significant improvement in yield or pest suppression or both.
- Operational advantages (ease of use, compatibility with existing systems).
- Regulatory compliance and environmental safety.

8.3.3 Regulatory and Registration

The regulatory and registration process seeks approval from regulatory bodies for the product to be available to the market as well as post-market compliance activities.

Successful registration of biopesticide products requires a comprehensive and well-coordinated approach that ensures regulatory compliance, product safety, and market readiness. Trials for the purpose of registration must consider country specific regulatory requirements and may entail the assessment of product performance under a variety of conditions (greenhouse, open-field), climatic regions, and across multiple years.

Regulatory Process: Have a clear understanding of the regulatory process and requirements for the relevant jurisdiction

Registration Studies: Conduct required studies on efficacy, residue, environmental fate, and toxicity, for example, if necessary for registration.

Data and Documentation: Provide genetic sequence information for microbials, verify lack of genes associated with toxicity.

Label Development: Create a clear and accurate product label with supportable claims and strategies to manage incompatibilities with other practices.

Stakeholders: Primary stakeholders are manufacturers, regulatory bodies (e.g., US EPA, State agencies), and various industry and trade groups.

8.3.4 Characteristics of registration trials

Registration requirements will differ by municipality and local regulations. As such, the following characteristics are generalisations rather than guidance for product registration.

- Core Registration Studies
- Clearly organised documentation to support regulatory review.
- Chemical and Product Characteristics with detailed profiles including composition, stability, and formulation.
- Product manufacturing process described in detail
- Demonstrated efficacy against target pests under relevant conditions as required.
- Data on residue levels and safety for food crops.
- Genetic sequencing data is required for microbial products to confirm identity and safety.

Regulatory clarity and accessibility

- Regulations should be transparent, accessible, and consistently applied across jurisdictions.
- Researchers and product developers should understand registration guidelines to streamline the approval process and reduce delays.

Environmental and toxicological considerations

- Data on persistence, mobility, and ecological impact in the environment over time.

- Toxicity safety assessments for human, animal, and non-target organism exposure, including the aquatic environment.

Data management and waivers

- Opportunities for data waivers should be explored where appropriate, especially for substantially similar microbial products.
- Use of existing data to support new registrations when products are comparable.

Label development

- Labels must clearly articulate product claims, usage instructions, and realistic expectations.
- Use of precise language enhances understanding and compliance.

Regulatory communication

- Effective communication between registrants and regulators is essential.
- Submissions must include high-quality data, be properly formatted, and accompanied by timely responses to regulatory queries.
- Guidelines for registration trials will vary and be provided by registration authority.

8.4 Production

The production stage focuses on scaling up manufacturing and ensuring a consistent product for commercial sale.

Scaling up biopesticide products from proof-of-concept to commercial production demands a coordinated approach across manufacturing infrastructure, formulation, regulatory compliance, and supply chain management. Central to this process is the availability of suitable fermentation systems that support both pilot and large-scale manufacturing, ensuring consistent product quality. Equally important are trials to ensure biopesticide product quality and efficacy is retained through scaled up production and data is collected to meet regulatory standards and guide proper usage, product labels must be clear, accurate, and fully compliant.

At this stage understanding of production costs informs investment and pricing strategies to support long-term commercial viability. Consistent supply hinges on securing reliable and sustainable sources of raw materials and inputs, while defined storage conditions and efficient distribution networks are essential to maintain product integrity and meet growing market demand.

Infrastructure: Secure the necessary infrastructure for scalability, such as fermenters for both proof of concept (POC) and commercial production.

Formulation and Logistics: Develop a stable formulation with a good shelf life, determine the cost of goods, and establish distribution channels.

Stakeholders: Key players are biotech companies, contract manufacturers, supply chain, and investors.

8.5 Commercial Grower Trials

Commercial-scale trials conducted on actual farms demonstrate the product's value and efficacy to growers in a real-world setting.

Effective trial design is essential when evaluating new biopesticide products to ensure results are reliable, relevant, and applicable to real-world conditions. Field trials, typically conducted in growers' fields by manufacturers in collaboration with local experts after the product has been registered, play a critical role in assessing product performance, compatibility with existing pesticide programmes, and site-specific factors such as soil, water quality, and crop rotation. Objective data collection and meaningful analysis from these trials inform decisions about market adoption, support grower education, and guide adaptation strategies, ultimately refining product use to ensure effectiveness and sustainability at a commercial scale.

> **Practical Application:** Consider commercial harvest requirements and use extension services to ensure growers apply protocols correctly.
>
> **Outcome Measurement:** Measure outcomes and track the product's compatibility with other pest or agronomy programmes.
>
> **Stakeholde**rs: This includes growers, technical representatives, pest control advisors (PCAs), and extension services.

8.5.1 Characteristics of commercial grower trials

When conducting field trials for biopesticide products, several practical and regulatory factors must be carefully managed to ensure meaningful results and compliance:

- Trials should have clear and specific questions or hypothesis
- Trials should align with commercial harvest schedules and meet quality and yield standards to avoid disruption to commercial operations
- Adequate plot size and replication are essential to capture variability and ensure statistically valid outcomes
- Trails should include true replication i.e. be designed to avoid pseudoreplication
- Have a specified minimum set of metadata that the experimenter should collect (to support interpretation for different contexts)
- Clear communication and training through extension or similar outreach services help growers apply trial protocols correctly and consistently
- All trial activities must adhere to label requirements and instructions, including worker protection standards such as personal protective equipment (PPE), specific mixing requirements or environmental considerations.
- Document what pest control or fertility practices are continued or withheld in the trial area to assess compatibility and integration within existing management programmes to isolate product effects.
- Use appropriate tools and technologies (e.g., sensors, imaging, data logging) to accurately measure trial outcomes and support data integrity.

- Trials should be designed to capture not only pest control efficacy but also direct impacts on farm productivity and profitability. This includes measuring yield, input costs, labour requirements, and any operational efficiencies or challenges.

8.6 Grower Adoption

Grower adoption ensures widespread and sustained use of the product by growers. To support successful adoption and industry confidence in novel pest management solutions, it is essential to provide clear, data-driven guidance, adapted to real-world conditions. This includes defining optimal usage parameters such as soil type, climate, and crop stage, and offering region-specific recommendations. Avoiding broad efficacy claims, integrating into existing IPM programmes, and transparently communicating expected variability and limitations can help manage grower expectations. Educational resources and simplified trial summaries further support informed decision-making. Ensuring consistent efficacy is the biggest hurdle to grower adoption for biological products. Ongoing collaboration among stakeholders and long-term validation across diverse environments are key to refining recommendations and strengthening product credibility.

Ease of Use: Focus on making the product easy to apply with existing farm equipment and compatible with current management practices (e.g. IPM).

Economics: Demonstrate the economic benefits to growers, such as equal or higher yields and compatibility with existing programmes.

Support and Education: Provide training and education to help growers and PCAs use the product effectively.

Stakeholders: Growers, PCAs, commodity groups, agronomists, and government agencies all play a role in promoting adoption.

To ensure successful adoption and performance of biological pest control solutions, the following considerations should guide product development, trailing, and grower engagement:

Programme Design and Application

- Engage growers and extension or extension related organisations early to ensure solutions are practical and aligned with field realities.
- Products should be compatible with existing equipment, irrigation and spray schedules, and require a manageable number of applications.
- Support flexible approaches that allow growers to adjust applications based on field conditions and performance feedback.

Performance and Integration

- Solutions must be cost-effective and deliver measurable benefits, such as equal or improved yields and reduced harm to non-target organisms.
- Biopesticides often require integration into a broader management programme involving multiple products and practices.
- Ensure products work within current IPM strategies and programmes.

Measurement and Impact

- Use technology and field data to track outcomes and validate effectiveness.
- Consider environmental impact and opportunities for carbon market qualification.

Adoption Strategy

- Recognise the 80:20 dynamic, most growers follow proven leaders. Focus efforts on early adopters to build momentum.
- Provide training through extension services, university programmes, and field advisors to educate on proper product use.
- Collaborate with government, retailers, and environmental advocates to offer incentives and promote sustainable practices.
- Prioritise testing of the most promising products under commercial conditions.

8.7 Post-Launch Development

After the product is launched, the work isn't over. Post-Launch Development involves continuously evaluating and improving the product.

Evaluation: Test the product in non-ideal use cases and evaluate its success under specific environmental or pest conditions.

Improvement: Improve formulation to increase adoption and integrate the product into new programmes or for new pests.

Stakeholders: Growers, manufacturers, IR-4, and extension services are crucial for this ongoing effort.

8.8 Market analysis – Constant throughout the pipeline

Market analysis is an ongoing activity informs every stage of the product development and commercialisation process.

Market Assessment: Continuously assess the target market, market size, and existing competition.

Strategic Planning: Address IP issues, calculate ROI, and consider whether the product will replace or integrate with existing solutions.

Stakeholders: Growers, retailers, investors, and supply chain stakeholders are all critical for market analysis.

9 Appendix 3: Exemplar assessment report

Biopesticide Report: Product, Pest/Disease, Crop

Introduction

Introduction to pest issue and objective of study to include pest of interest, products evaluated, and hypothesis.

Trial location, site description to include soil type and conditions (C/N/P/K, pH, CEC, etc), water quality, and daily temperature

Metrics used for evaluation

Data collected to evaluate product application success (disease severity, insect count, etc.)

Degree of control, describe parameters for success. See “efficacy” discussion.

Abstract

Summary of trial narrative and results.

Data

Include actual quantitative data, such as yield in crop-specific terms (for example, if traditionally harvested in tons per hectare/acre, or boxes per hectare/acre, convert for consistency, or number of marketable units). All trial reports must include at least one farm productivity metric (e.g. yield per hectare/acre, input cost per hectare/acre, number of spray passes, or labour hours saved), and a summary of Year 1 ROI for the grower.

Statistical analysis is highly preferred and percent difference, only reporting means, or other proxy representations of data should not be considered ‘primary data’. Include mean values, standard errors of the means.

Present data in tables to include columns for treatments, relevant data collected at key points, and any notes. Graphical charts are acceptable but should be supplementary rather than replace table format.

Trial Design and Methods

Trial size, crop rotation history, use of mulch, plant spacing, seed or transplant variety, irrigation regime, nutrient regime and application method, and trial design (if any).

Treatment rate, dates, and application method (e.g. sprayer type, PSI, nozzle).

Results and Conclusion

Objective reporting of results and comments to enhance crop and geographic fit. Resources such as ‘Arthropod Management Tests’ or ‘Plant Disease Management Reports’, can provide examples of effective reports.

10 Appendix 4: Food Safety

Food Safety is a critical component to crop inputs for fresh fruits and vegetables, which are often eaten raw or with minimal processing. Managing food safety risk is critical when using biopesticides on fresh produce, as biopesticides may have live microorganisms or biological agents. Growers and product registrants should incorporate the following guidelines into their trialling and operational protocols:

Regulatory Compliance

- Confirm that the biopesticide products are registered and approved by relevant regulatory bodies. Confirm MOA, label claims, and safety data have been evaluated in accordance with relevant regulatory bodies.
- Clearly document adherence to pre-harvest intervals (PHIs) as stated on product labels. MRLs are legally binding thresholds when established by regulatory authorities. PHIs, which are mandatory use directions on the pesticide label, specify the minimum time between the last application and harvest and are designed to ensure that residues at harvest remain below the established MRLs.

Microbial Safety

- Regularly verify microbial purity and ensure biopesticide products are free from human pathogens such as *Salmonella*, pathogenic *Escherichi coli*, and *Listeria*. Regulatory guidance may emphasise that microbial pest control agents must be demonstrated to be safe for human health, including an infectivity and pathogenicity analysis.
- Consider establishing routine, statistically valid testing protocols to verify that biopesticide products consistently meet established safety and quality standards. Sampling strategies should be representative of the production lot and designed with sufficient detection power to identify potential contamination or deviations in product quality.
- Resources such as the California and Arizona Leafy Greens Marketing Agreements (LGMA) provide detailed food safety practices that support decision-making on microbial risks, including those associated with crop inputs such as biopesticides. International frameworks such as Guidelines for Microbial Biopesticides can also be additional resources.

Documentation and Traceability

- Maintain detailed application records, including batch numbers, application rates, dates, and personnel involved in applying biopesticides.
- Ensure full traceability from product sourcing through to harvest.
- Maintain detailed product quality records, for example, under U.S. law (40 CFR Part 158, Subpart V), registrants of microbial pesticides must document and maintain data demonstrating product identity, microbial purity, absence of human pathogens, stability, and performance. These data requirements form the basis for EPA’s risk assessments and product registration decisions.

Cross-Contamination Prevention

- When applying biopesticides, biostimulants, or other inputs via fertigation/chemigation, applicators should carefully evaluate potential food safety risks.

- Clearly specify buffer zones and other physical or temporal separation strategies to prevent contamination of edible portions of crops.
- Ensure proper cleaning and sanitation of application equipment to prevent contamination risks.
- Verify that the water source used for tank mixes meets microbial safety standards, such as CA LGMA standards.

Training and Education

- Provide comprehensive training to field personnel on correct product handling, application methods, and hygiene standards specific to biopesticide use.
- Regularly update training materials and include food safety protocols as integral components of biopesticide product use education.

Risk Communication

- Transparently communicate any known or potential risks associated with biopesticides to stakeholders, clearly outlining safe handling practices, storage conditions, and emergency response actions.

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Bioeconomy Science Institute,

The Bioeconomy Science Institute conducts research to advance innovation in agriculture, horticulture, aquaculture, forestry, biotechnology and manufacturing, to protect and enhance ecosystems from biosecurity threats and climate risks; and develop new bio-based technologies and products. The Bioeconomy Science Institute was formed on 1 July 2025, bringing together AgResearch, Manaaki Whenua - Landcare Research, Plant & Food Research and Scion into a single organisation.

Western Growers

Founded in 1926, Western Growers is a non-profit agricultural trade association that represents local and regional family farmers growing fresh produce in Arizona, California, Colorado and New Mexico. Our members and their workers provide over half the nation's fresh fruits, vegetables and tree nuts, including nearly half of America's fresh organic produce.

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