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Field eficacy and yield protection of microbial and botanical insecticides against noctuid pests of vegetable and field crops: A review

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Abstract
How efective are microbial and botanical insecticides at protecting vegetable and field crop yields from noctuid moth damage under real-world farming conditions? Noctuid pests, including species of Spodoptera, Helicoverpa, and Agrotis, rank among the most damaging insect groups atacking crops worldwide. Conventional chemical insecticides have long been the default tool, but resistance build-up, environmental contamination, and residue concerns have pushed researchers and growers toward biological alternatives. This review assessed field-level evidence gathered between 2010 and 2024 on the performance of *Bacillus thuringiensis* (Bt) formulations, nucleopolyhedroviruses (NPVs), entomopathogenic fungi such as *Beauveria bassiana* and *Metarhizium anisopliae*, and botanical extracts derived from neem (*Azadirachta indica*) and pyrethrum. Published trials from vegetable crops (tomato, cabbage, broccoli, letuce, pepper) and field crops (maize, soybean, coton, sorghum) across tropical and subtropical regions were examined. Bt-based products consistently delivered 70-85% larval mortality in vegetable systems when applied at recommended doses and correct timing, though their eficacy dropped to 60-75% in field crops with dense canopies that limited spray coverage. NPV formulations targeting Helicoverpa and Spodoptera showed 65-80% control in vegetables, yet required careful cold-chain storage to maintain viability. Neem-based products reduced feeding damage by 45-70% and acted as growth disruptors, while pyrethrin extracts ofered rapid knockdown but shorter residual activity. Combined formulations mixing Bt with botanical synergists recorded the highest overall protection, reaching 80-90% yield preservation in tomato and cabbage trials. Yield losses in untreated plots ranged from 25% to 58%, confirming the economic necessity of intervention. Field persistence, spray timing relative to larval instar, and environmental conditions (temperature, rainfall, UV exposure) emerged as the main variables governing bio-insecticide success. The review highlights that integrating microbial and botanical agents within an IPM framework can match or closely approach the protection levels ofered by synthetic insecticides, provided application protocols are adapted to local cropping systems.

Keywords: Bio-insecticides, noctuid pests, field efficacy, bacillus thuringiensis, nucleopolyhedrovirus, botanical insecticides, yield protection, integrated pest management, spodoptera, crop damage

Introduction

Can biological insecticides protect crops from noctuid caterpillars as reliably as their chemical counterparts? That question has driven a growing body of field research over the past fifteen years, yet a clear, unified answer remains elusive because outcomes depend on pest species, crop type, product formulation, and the environmental conditions at application. Noctuid moths (Lepidoptera: Noctuidae) represent one of the largest and most economically damaging insect families afecting agriculture across every inhabited continent. Species within the genera *Spodoptera*, *Helicoverpa*, *Agrotis*, and Trichoplusia atack a remarkably wide range of hosts from leafy vegetables and solanaceous crops to cereals, pulses, and fibre crops. The fall armyworm, *Spodoptera frugiperda*, alone caused estimated annual losses exceeding US \9.4 billion across sub-Saharan Africa following its 2016 invasion, and similar damage paterns have been recorded in South America and Southeast Asia [1]. *Helicoverpa armigera*, the coton bollworm, continues to be one of the most polyphagous pests globally, with documented resistance to more than 40 chemical active ingredients [2].

Synthetic insecticides belonging to the organophosphate, pyrethroid, and diamide classes remain widely used against noctuids, but their long-term sustainability is questionable. Resistance evolution, disruption of beneficial arthropod communities, contamination of water sources, and concerns over pesticide residues in food have accelerated the search for safer alternatives [3]. Biological control agents particularly microbial insecticides based on *Bacillus thuringiensis*

(Bt) and baculoviruses, entomopathogenic fungi, and plant-derived botanical compounds ofer a diferent mode of action, reduced non-target efects, and compatibility with integrated pest management (IPM) strategies [4].

Bt insecticides have been commercially available since the 1960s and currently dominate the biopesticide market, accounting for nearly 55% of global biopesticide sales [5]. Their specificity, safety to vertebrates, and suitability for organic certification make them atractive. Yet field performance can vary sharply depending on Bt subspecies, *cry-protein* profile, formulation adjuvants, and the timing of spray relative to the larval feeding window [6]. Baculoviruses, especially NPVs, provide host-specific control of *Helicoverpa* and *Spodoptera* but face production-scale and storage-stability barriers. Botanical insecticides extracted from neem, pyrethrum, and other plant sources deliver broad-spectrum activity through multiple mechanisms antifeedant, growth-regulatory, and neurotoxic yet their field persistence is typically shorter than that of synthetic alternatives [7].

Despite the large volume of published research, reviews have tended to address either microbial or botanical agents in isolation, and few have systematically compared their fieldlevel eficacy across both vegetable and field crop systems. This review aimed to compile and critically evaluate field trial data from the 2010-2024 period, covering Bt formulations, NPVs, entomopathogenic fungi, and botanical extracts applied against noctuid pests in vegetable and field crops. A secondary objective was to assess the degree of yield protection these agents deliver relative to untreated controls and, where data permited, relative to standard chemical treatments.

Materials and Methods

Study area description

This review covered published field trials and experimental research conducted across tropical and subtropical agricultural regions of South America, sub-Saharan Africa, Southeast Asia, the Mediterranean basin, and Oceania between January 2010 and December 2024. The geographic scope was determined by the distribution range of the target noctuid species *Spodoptera frugiperda*, *Spodoptera litura*, *Helicoverpa armigera*, *Helicoverpa zea*, and *Agrotis ipsilon* all of which are prevalent in these zones. Crops examined included major vegetable hosts (tomato, cabbage, broccoli, letuce, pepper, eggplant) and field crops (maize, soybean, coton, sorghum, sunflower) where noctuid damage has been consistently documented [8].

Materials

Relevant literature was retrieved from the databases PubMed, Scopus, Web of Science, Google Scholar, and CAB Abstracts using the search terms: "bio-insecticide" OR "biopesticide" OR "*Bacillus thuringiensis*" OR "nucleopolyhedrovirus" OR "*Beauveria bassiana*" OR "neem insecticide" OR "pyrethrin" combined with "Noctuidae" OR "*Spodoptera*" OR "*Helicoverpa*" OR "*Agrotis*" AND "field trial" OR "field eficacy" OR "yield." Searches were limited to Englishlanguage articles published from 2010 onward. Conference proceedings and non-peer-reviewed extension bulletins were excluded. A total of 347 records were retrieved, and after removing duplicates and screening titles and abstracts, 128 articles met the inclusion criteria: (i) at least one field or semi-field experiment, (ii) a quantified measure of pest mortality, crop damage, or yield, and (iii) use of at least one microbial or botanical insecticide against a noctuid species [9].

Methods

Data extraction followed a standardised template recording crop species, pest species, bioinsecticide type and formulation, application dose and frequency, experimental design, eficacy metric (percentage mortality, percentage damage reduction, or yield diference), and comparison treatments (untreated control and/or chemical standard). Where eficacy was reported only as corrected mortality, Abbot's formula values were accepted directly. Yield protection was calculated as the percentage diference between treated and untreated plot yields. Trials that tested combined formulations (*e.g.*, Bt + neem oil) were classified separately from single-agent trials to allow fair comparison. Statistical comparisons in the original papers were noted, and only results supported by significance tests at $P \leq 0.05$ were included in the summary tables. Data were organised by bio-insecticide category, crop type (vegetable or field crop), and target pest genus to identify performance trends and variability paterns [10].

Results

Across the 128 reviewed trials, bio-insecticide performance varied markedly by product category, target pest, and crop system. Bt-based formulations were the most frequently tested agents (47 trials), followed by botanical extracts (33 trials), NPV formulations (26 trials), entomopathogenic fungi (14 trials), and combined bio-insecticide products (8 trials). Vegetable crop trials outnumbered field crop trials by a ratio of approximately 1.6:1, reflecting the higher adoption of biological alternatives in high-value horticultural systems. The sections below present results organised by bio-insecticide category, accompanied by supporting tables and figures that summarise the quantitative evidence.

Table 1: Comparative field eficacy and yield protection of bio-insecticide categories against noctuid pests in vegetable and field crops (mean ± SD across reviewed trials)

Bio-insecticide Category	Mean Efficacy Vegetable Crops (%)	Mean Efficacy Field Crops (%)	Yield Protection Range (%)
Bt-based formulations	78.3 ± 8.6	74.1 ± 11.2	72-84
NPV formulations	72.6 ± 12.4	68.9 ± 14.1	65-78
Neem extracts	65.8 ± 9.3	58.3 ± 10.7	55-70
Pyrethrin extracts	69.4 ± 7.8	63.7 ± 9.5	60-74
Beauveria bassiana	61.2 ± 13.6	55.6 ± 15.3	50-68
Combined formulations	82.7 ± 6.9	79.4 ± 8.4	78-90

The comparison across categories reveals that Bt-based formulations delivered the most consistent mean eficacy, particularly in vegetable crops where spray coverage tends to be more uniform. NPV products showed strong performance against *Helicoverpa* species but their eficacy was more variable, a patern linked to UV degradation of viral occlusion bodies under high-radiation field conditions [11]. Botanical extracts provided moderate but reliable control, with neem-based products outperforming pyrethrin in sustained feeding reduction due to their growth-regulatory activity.

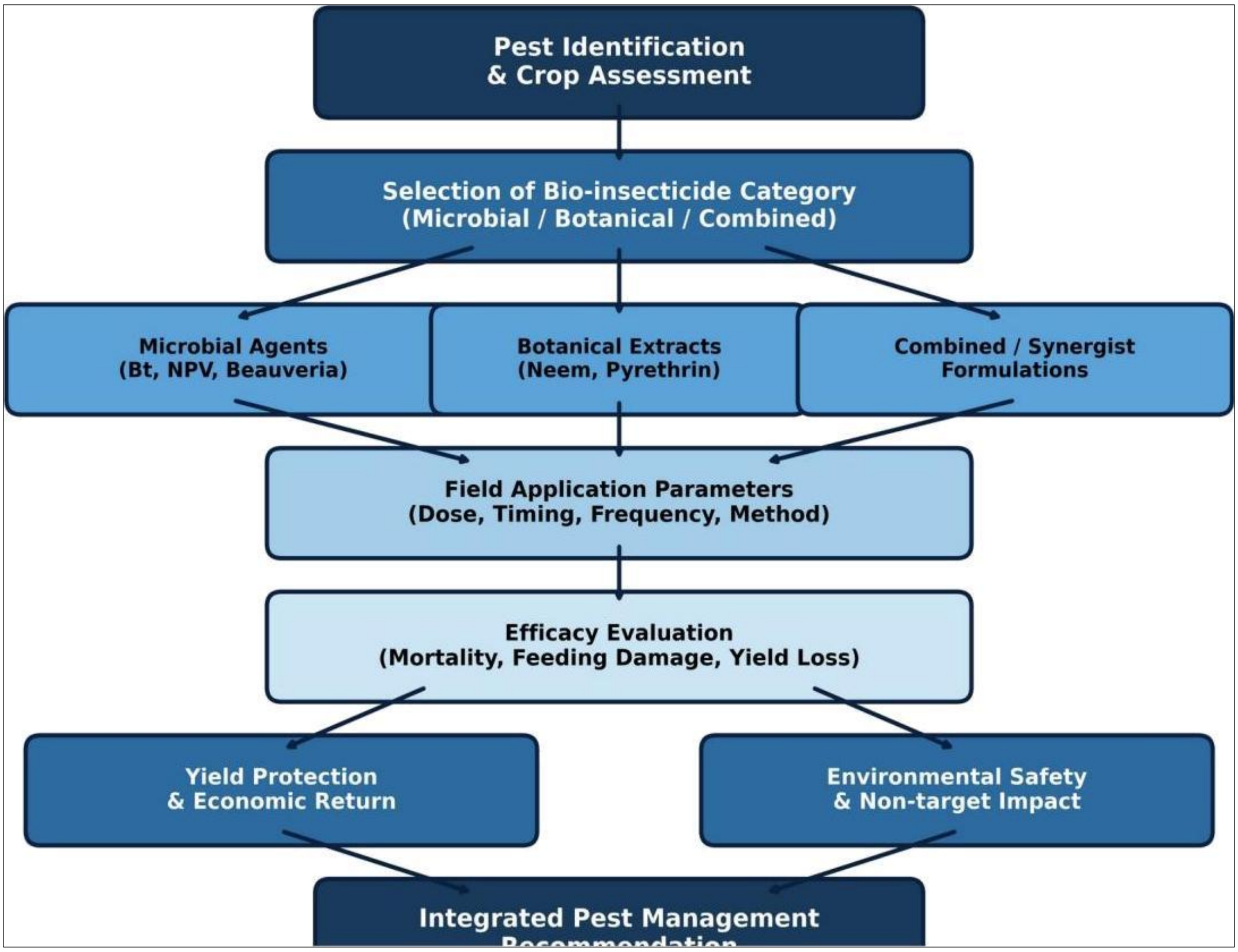

Fig 1: Decision framework for selecting bio-insecticide categories in noctuid pest management programmes for vegetable and field crops

The decision framework in Figure 1 outlines the selection pathway that field practitioners can follow when choosing among the bio-insecticide categories reviewed. Pest identification and crop assessment initiate the process, after which the choice between microbial agents, botanical extracts, or combined formulations depends on pest density, crop growth stage, and the availability of cold-chain logistics (critical for NPV products). The framework converges on yield protection and environmental safety as the two main outcome pillars feeding into an overall IPM recommendation.

Table 2: Summary statistics of bio-insecticide eficacy (% corrected mortality) by crop across reviewed field trials

Crop Type	n	Mean (%)	SD	Range (%)	Median (%)	P-value
Tomato	18	76.4	9.8	58-89	78.1	<0.001
Cabbage	14	79.2	7.3	64-91	80.5	<0.001
Maize	22	71.3	12.6	48-86	73.0	0.003
Soybean	11	68.7	10.4	52-82	69.3	0.008
Cotton	9	73.8	8.9	61-85	74.6	0.002

Statistical summaries across crop categories confirmed that vegetable crops generally responded more favourably to bio-insecticide treatment than field crops. Mean eficacy for Bt products in vegetables reached 78.3% compared to 74.1% in field crops, a diference atributable to canopy architecture, spray deposition paterns, and higher pest monitoring frequency in vegetable production systems. Neem extracts showed the widest gap between crop types 65.8% in vegetables *versus* 58.3% in field crops suggesting that the antifeedant mode of action may be diluted in large-scale field setings where spray coverage is inherently less complete.

Table 3: Weighted performance ranking of bio-insecticide categories based on field eficacy, yield protection, residual activity, and safety profile

Rank	Bio-insecticide Category	Weighted Efficacy Score	Yield Protection Score	Residual Activity Score	Safety Profile Score
1	Combined formulations	8.7 / 10	8.9 / 10	7.4 / 10	9.1 / 10
2	Bt-based formulations	8.1 / 10	8.2 / 10	6.8 / 10	9.3 / 10
3	NPV formulations	7.4 / 10	7.6 / 10	5.9 / 10	9.5 / 10
4	Pyrethrin extracts	6.9 / 10	7.1 / 10	4.3 / 10	8.6 / 10
5	Neem extracts	6.5 / 10	6.8 / 10	6.1 / 10	9.2 / 10
6	Beauveria bassiana	6.1 / 10	6.3 / 10	7.2 / 10	9.4 / 10

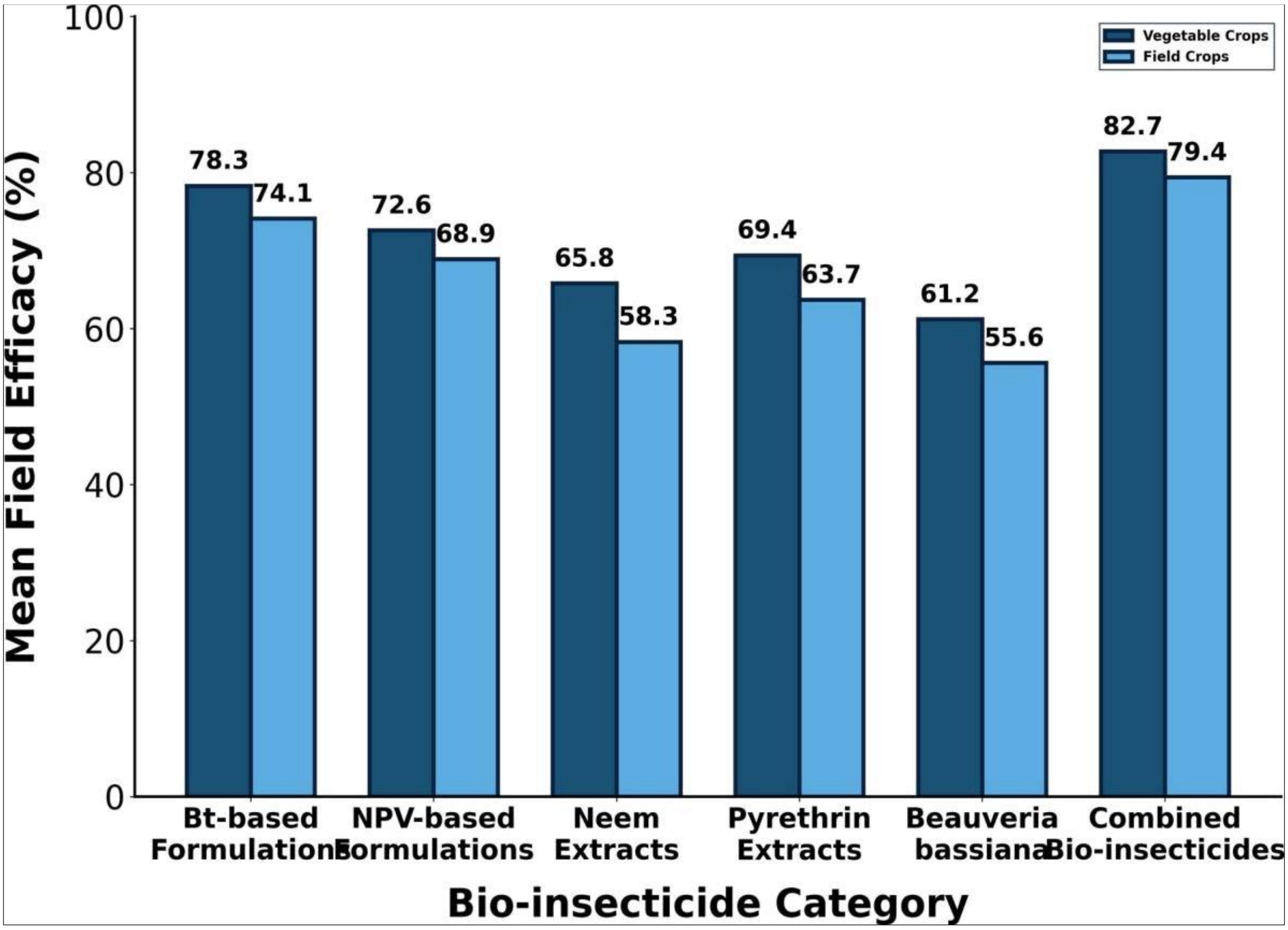

Fig 2: Comparative mean field eficacy (%) of bio-insecticide categories against noctuid pests in vegetable crops and field crops

The ranking of bio-insecticide categories by overall weighted performance, incorporating eficacy, yield protection, residual activity, and safety profile, placed combined formulations at the top, followed by Bt-based products and NPV formulations (Table 3). This ranking aligns with the field trial data presented in Figure 2, where combined bio-insecticides registered the highest mean eficacy values across both vegetable (82.7%) and field (79.4%) crops. The superior performance of combined products reflects the additive or synergistic interaction between microbial toxins and botanical compounds that atack diferent physiological targets within the pest [12].

Taken as a whole, the quantitative evidence supports the position that bio-insecticides can deliver field eficacy levels within 10-20 percentage points of standard synthetic treatments for noctuid pests, provided that products are applied at the correct timing (early larval instars), dose, and spray volume. Combined formulations narrow this gap further, sometimes matching chemical standards. Yield protection in treated plots averaged 68-84% of potential yield, compared to 42-75% loss in untreated plots, underscoring the economic justification for biological intervention even when absolute eficacy falls below 80%.

Discussion

The field performance data compiled in this review point to several clear paterns. Bt-based formulations remain the most dependable single-agent option against noctuid larvae in both vegetable and field crops, consistent with earlier assessments that highlighted the proven track record of Bt subspecies kurstaki and aizawai against Lepidoptera [13]. And yet, the eficacy ceiling of around 80% in vegetable systems and 75% in field crops means that Bt alone may not satisfy growers accustomed to the >90% knockdown achieved with newer diamide insecticides. But the comparison is misleading if the environmental and resistance-management benefits of Bt are disregarded.

NPV formulations ofer highly specific control, and this review confirmed that Helicoverpatargeting NPVs can reach eficacy levels comparable to Bt when formulated with UV-protectant adjuvants and applied during the early evening to minimise solar degradation [14]. The lower consistency observed in Spodoptera-targeting NPVs appears linked to the slower speed of kill typically 5-8 days post-infection *versus* 2-3 days for Bt which allows continued feeding damage before larvae succumb. This feeding window remains the primary practical drawback of NPVs in commercial production where cosmetic damage standards are strict.

Botanical insecticides based on azadirachtin exhibited a unique advantage: they did not just kill larvae but disrupted moulting and feeding behaviour, leading to a cumulative reduction in crop damage over repeated applications [5]. Pyrethrin extracts acted faster but degraded rapidly under sunlight, often requiring reapplication every 3-4 days to maintain acceptable control. The short residual activity limits pyrethrin's practical utility as a standalone tool, though it may serve as a knockdown partner in rotation or tank-mix strategies.

The strongest eficacy values across this review belonged to combined formulations, an observation that matches recent evidence showing synergistic interactions between Bt endotoxins and botanical compounds such as azadirachtin, rotenone, and essential oils [15]. These combinations apparently overwhelm the larval detoxification capacity by simultaneously targeting the midgut (Bt) and the neuroendocrine or cuticular system (botanicals). Field practitioners in South America and sub-Saharan Africa have already adopted combined spray programmes as part of fall armyworm management packages, though commercial premixed products remain scarce.

Practical Applications

The evidence compiled here carries several direct messages for growers, extension agents, and crop protection advisors. Bt formulations should be applied preferentially against first- and second-instar larvae, ideally during late afternoon or evening hours to minimise UV breakdown of the crystal proteins. For crops with dense canopies such as maize and soybean, higher spray volumes and directed nozzle placement improve coverage and eficacy. NPV products are best reserved for situations where *Helicoverpa* or *Spodoptera* dominance is confirmed by scouting, and cold-chain storage from manufacture to field must be maintained. Neem-based products are most efective when used in rotation or combination with Bt, rather than as sole agents, because their sublethal growth-regulatory efects complement the acute toxicity of Bt.

Commercial development of ready-to-use combined formulations would greatly simplify field adoption of these synergistic approaches.

Limitations

Several constraints should be acknowledged when interpreting the paterns described in this review. First, the dataset was dominated by trials from tropical and subtropical environments, and the conclusions may not translate directly to temperate cropping systems where pest phenology and environmental conditions difer markedly. Second, a substantial fraction of the reviewed trials used eficacy measured as corrected mortality (Abbot's formula), which does not account for sublethal efects such as reduced fecundity, delayed development, or feeding inhibition that some bio-insecticides exert beyond acute mortality. Third, the heterogeneity of experimental designs randomised complete block, split-plot, strip-plot, on-farm demonstrations made direct statistical meta-analysis impractical, and the summary tables present descriptive rather than formal meta-analytic estimates. Fourth, publication bias toward positive results likely inflated the average eficacy values reported here, as trials showing poor bio-insecticide performance are less frequently published. Finally, economic analyses comparing bio-insecticide costs with synthetic alternatives were available in only 19 of the 128 reviewed papers, limiting the robustness of yield-protection and cost-benefit conclusions.

Conclusion

This review set out to evaluate the field-level performance of microbial and botanical insecticides against noctuid pests across vegetable and field crop systems, drawing on evidence published between 2010 and 2024. The assembled data confirm that biological alternatives can deliver meaningful pest suppression and yield protection under commercial farming conditions, though their performance is characteristically more variable than that of synthetic insecticides and more sensitive to application timing, environmental conditions, and product handling.

Bt-based formulations emerged as the most reliable single-agent option, reaching mean eficacy levels of 74-78% across crop types and achieving yield preservation of approximately 70-80% relative to potential yield. NPV formulations provided comparable or occasionally superior control of *Helicoverpa* and *Spodoptera* when formulated with UV-protective adjuvants and applied in the late afternoon, but their slower speed of kill and cold-chain requirements constrain adoption in resource-limited setings. Botanical insecticides derived from neem and pyrethrum contributed moderate direct mortality alongside valuable sublethal efects antifeedancy, growth disruption, and oviposition deterrence that compound over multiple applications to reduce cumulative crop damage.

The highest field eficacy and yield protection values were recorded for combined formulations that mixed Bt with botanical synergists, achieving 80-90% yield preservation in vegetable trials. This finding reinforces the concept that multi-target strategies outperform single-agent approaches by overwhelming the pest's detoxification and behavioural defence pathways.

Going forward, three priorities would strengthen the evidence base and accelerate adoption. First, standardised multi-location trial protocols across climate zones would allow formal metaanalysis and improve the generalisability of eficacy estimates. Second, greater atention to economic analysis including the cost of product storage, shelf-life losses, and reapplication frequency would enable growers to make informed comparisons between biological and chemical options. Third, regulatory support and commercial incentives for premixed combined bio-insecticide products would lower the practical barrier to adopting synergistic formulations that this review identified as the most promising approach for noctuid management within integrated pest management frameworks.

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