FALL ARMYWORM BIOLOGICAL CONTROL: EVIDENCE, RESEARCH GAPS, AND IMPLEMENTATION PRIORITIES

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Abstract

Background: Biological control is increasingly promoted for fall armyworm, Spodoptera frugiperda, but recent evidence remains dispersed from natural-enemy discovery to farmer adoption. Objective: This narrative review synthesized open-access Scopus articles indexed as 2026 publications and available through 2 July 2026, assessing evidence maturity toward implementation. Methods: Of 45 Agricultural and Biological Sciences records, 13 full texts were retrieved; 12 articles were included and synthesized thematically. Results: Parasitoids and entomopathogens showed promising controlled efficacy, but field performance varied. Combining Telenomus remus, Beauveria bassiana, and Metarhabditis rainai increased larval mortality and crop performance, whereas baculovirus products underperformed synthetic insecticides. Major gaps involved multi-season validation, standardized crop and economic outcomes, ecological safety, mass production, and sustained adoption. Conclusion: Research should prioritize translating biological efficacy into reliable, measurable, and scalable management strategies.

Keywords: *Biological Control; Fall Armyworm; Entomopathogens; Parasitoids; Implementation Readiness*

Abstrak

Latar belakang: Pengendalian hayati semakin dipromosikan untuk ulat grayak jagung, *Spodoptera frugiperda*, tetapi bukti terbaru tersebar dari penemuan musuh alami hingga adopsi petani. Tujuan: Tinjauan naratif ini menyintesis artikel akses terbuka Scopus terbitan 2026 yang tersedia hingga 2 Juli 2026 dan menilai kematangan bukti menuju implementasi. Metode: Dari 45 rekaman bidang Agricultural and Biological Sciences, 13 teks lengkap diperoleh; 12 artikel dimasukkan dan disintesis secara tematik. Hasil: Parasitoid dan entomopatogen menunjukkan efikasi terkendali yang menjanjikan, tetapi kinerja lapangan bervariasi. Kombinasi *Telenomus remus*, *Beauveria bassiana*, dan *Metarhabditis rainai* meningkatkan mortalitas larva dan kinerja tanaman, sedangkan produk bakulovirus kurang efektif dibandingkan insektisida sintetis. Kesenjangan utama mencakup validasi multimusim, hasil tanaman dan ekonomi yang terstandar, keamanan ekologis, produksi massal, serta adopsi berkelanjutan. Simpulan: Prioritas riset perlu diarahkan pada penerjemahan efikasi biologis menjadi strategi yang andal, terukur, dan dapat diterapkan.

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Kata Kunci: *Pengendalian Hayati; Ulat Grayak Jagung; Entomopatogen; Parasitoid; Kesiapan Implementasi*

A. Introduction

Fall armyworm, *Spodoptera frugiperda*, is a highly mobile and polyphagous lepidopteran pest that has become a persistent constraint in maize and other crop systems across its native and invaded ranges. The pest is difficult to suppress because larvae often feed within protected plant structures, populations can migrate over long distances, and resistance has developed to several insecticide and *Bacillus thuringiensis* traits. The continued dependence on repeated chemical applications also threatens natural enemies, environmental quality, and the durability of integrated pest management programs (Giacomelli et al., 2026; Herlinda et al., 2026; Senousy et al., 2026).

Biological control offers several complementary pathways. Natural regulation can be provided by parasitoids, predators, fungi, viruses, bacteria, and nematodes. Augmentative programs can release mass-reared parasitoids or apply microbial agents, while conservation biological control can manipulate crop diversity and habitat to retain or recruit beneficial organisms. Endophytic entomopathogenic fungi add a further mechanism by colonizing plant tissues and affecting herbivore survival without depending exclusively on direct foliar contact (Herlinda et al., 2026).

Despite broad interest, evidence is fragmented by biological-control category and experimental scale. Some studies document a new parasitoid or pathogen association, others quantify virulence under controlled conditions, and a smaller group evaluates crop damage, yield, compatibility among agents, or farmer implementation. These forms of evidence answer different questions and should not be treated as equivalent. A natural-enemy record establishes ecological association, whereas operational biological control requires repeatable suppression, crop protection, feasible production and delivery, acceptable non-target effects, and adoption under real farming conditions.

The 2026 open-access literature illustrates this fragmentation. Laboratory studies report high fungal pathogenicity and identify host traits that shape parasitoid success. Field studies show both encouraging benefits from combined biological agents and disappointing performance of viral products under high pest pressure. Behavioral studies reveal that companion-plant volatiles may recruit parasitoids, but plant- and microbe-induced volatile changes can also reduce predator attraction. Separate studies address mass-rearing feasibility and the institutional conditions required for collective conservation biological control (Durocher-Granger et al., 2026; Pec et al., 2026; Peter et al., 2026; Shi et al., 2026).

A useful synthesis therefore needs to move beyond cataloguing agents. It should assess where each study sits between discovery and implementation

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and identify the missing transitions that prevent promising agents from becoming reliable management tools. The research gap addressed here is the absence of an integrated reading of recent FAW biological-control evidence that simultaneously considers efficacy, ecological context, crop-level outcomes, production feasibility, and social implementation.

This narrative review aimed to: (1) determine which of the supplied 2026 open-access studies were eligible for a focused review of FAW biological control; (2) synthesize evidence on parasitoids, predators, entomopathogens, microbial pesticides, and conservation biological control; (3) compare laboratory promise with field effectiveness and implementation readiness; and (4) identify research priorities. Its novelty lies in applying an evidence-to-implementation continuum that distinguishes agent discovery, controlled efficacy, field validation, crop and economic benefit, scalable production, and sustained adoption.

B. Methodology

Review design and information source

A structured narrative-review design was used. The information source was Scopus, with filters for publication year 2026, document type Article, English language, Open Access, and the Agricultural and Biological Sciences subject area. The search was performed on 2 July 2026. The initial search identified 115 records, and 45 remained after all database filters were applied. Full texts were retrieved for 13 articles, which formed the assessable corpus. Because the review was narrative rather than systematic, the objective was a transparent and critical thematic synthesis rather than an exhaustive estimate of effect size.

Search Strategy

To preserve traceability with the reported search results, the following expression is recorded exactly as it was executed in Scopus. The result counts reported in this article refer to this expression and to the sequence of filters applied through the Scopus interface:

TITLE-ABS-KEY ("*Spodoptera frugiperda*" OR "fall armyworm" OR "fall army worm" AND "biological control" OR biocontrol OR "natural enem" OR parasitoid OR parasitism OR predator OR predation OR entomopathogen OR "microbial control" OR biopesticid OR bioinsecticid OR baculovirus OR nucleopolyhedrovirus OR "entomopathogenic fung" OR "entomopathogenic nematod" OR "conservation biological control" OR "augmentative biological control" OR "classical biological control") AND PUBYEAR > 2025 AND PUBYEAR < 2027 AND (LIMIT-TO (OA, "all")) AND (LIMIT-TO (SUBJAREA, "AGRI")) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English"))

Sequential filtering yielded 2026 records (n = 115), articles (n = 105), English-language articles (n = 102), all Open Access records (n = 60), and Agricultural and Biological Sciences records (n = 45). Full texts were retrieved for 13 of the 45 records (28.9%), whereas 32 records (71.1%) could not be retrieved through the access routes used and were therefore not assessed for eligibility. The executed search expression did not fully group the FAW concept and the biological-control concept, and several terms were entered without wildcards. These characteristics may have affected the breadth and precision of the retrieved records. Nevertheless, because this study was designed as a structured narrative review rather than an exhaustive systematic review, the synthesis was conducted using the original search results and the full-text articles that were successfully retrieved.

Search flow: records assigned to 2026 (n = 115); articles (n = 105); English-language articles (n = 102); Open Access records (n = 60); Agricultural and Biological Sciences records (n = 45); full texts retrieved (n = 13); included (n = 12); and excluded after full-text assessment (n = 1).

Eligibility criteria and study selection

Original journal articles were eligible when they directly investigated biological control of *Spodoptera frugiperda* or an enabling component required for implementation. Eligible topics included parasitoid or predator occurrence and performance, entomopathogenic fungi or nematodes, baculovirus-based products, compatibility among biological agents, conservation biological control, natural-enemy recruitment, mass rearing, non-target or beneficial-insect compatibility, and farmer or community adoption. Laboratory, greenhouse, semi-field, field, ecological-survey, and social-science designs were considered.

Records were excluded when FAW was only an incidental organism and the study objective, analysis, and conclusions concerned another pest. Reviews, editorials, conference abstracts, and papers without sufficient outcome information would also have been excluded. Based on these criteria, 12 of 13 supplied records were retained. The study by Avellar et al. (2026) was excluded because its primary focus was *Melanaphis sorghi* population dynamics; FAW appeared only as a secondary pest with weak associations and no direct FAW biological-control outcome.

Data extraction and thematic synthesis

For each included study, data were extracted on country or study context, crop, biological-control category, agent, study design, experimental scale, principal outcome, implementation implication, and limitation. The synthesis combined deductive coding based on biological-control theory with inductive coding of recurring barriers. Deductive categories were parasitoid control, predator-mediated control, microbial control, conservation biological control, and augmentative implementation. Inductive categories included host-stage dependence, climatic and crop-context dependence, formulation and delivery, non-target compatibility, mass-rearing feasibility, field inconsistency, coordination, and farmer adoption.

Evidence maturity was interpreted along six levels: Level 1, natural-enemy discovery or association; Level 2, laboratory characterization or mechanism; Level 3, controlled efficacy; Level 4, field validation and crop protection; Level 5, scalable production, delivery, or economic feasibility; and Level 6, operational or community adoption. The synthesis was narrative because agents, designs, comparators, crops, and outcomes were too heterogeneous for statistical pooling.

C. Results and Discussions

Eligibility and characteristics of the evidence base

The Scopus search identified 115 records assigned to 2026. Restricting the results to articles retained 105 records, the English-language filter retained 102, the Open Access filter retained 60, and restriction to Agricultural and Biological Sciences yielded 45 records. Full texts were retrieved for 13 of the 45 records (28.9%). Thirty-two records were not assessed because their full texts could not be retrieved through the access routes used; these records were categorized as not retrieved rather than ineligible. Of the 13 articles assessed in full, 12 met the eligibility criteria and one was excluded because its primary focus was *Melanaphis sorghi* population dynamics. As shown in Table 1, the included evidence covered national or regional contexts in Africa, Asia, the Americas, and Oceania and represented a wide range of biological-control approaches, study settings, and analytical roles. Four studies were predominantly laboratory or mechanistic, three generated direct field-efficacy evidence, two documented natural-enemy occurrence or parasitism in field populations, one evaluated beneficial-insect compatibility, one addressed mass rearing, and one examined farmer knowledge and collective implementation. The eligibility decisions, study contexts, evidence settings, and specific contributions of each article to the narrative synthesis are summarized in Table 1. This distribution demonstrates broad thematic coverage but also substantial heterogeneity.

Table 1. Eligibility Decisions, Study Characteristics, And Analytical Roles Of The 13 Full-Text Records Assessed For Inclusion.

Study	Context	Primary focus	Evidence setting	Decision	Role in synthesis
Herlinda et al. (2026)	Indonesia; maize	Endophytic *Beauveria bassiana* inoculation methods and egg-parasitoid compatibility	Field plus laboratory feeding assay	Include - core	Microbial control; delivery method; compatibility
Senousy et al. (2026)	Egypt; laboratory	Indigenous entomopathogenic fungi and	Laboratory pathogenicity and chemistry	Include - core	Microbial efficacy and mechanism

Study	Context	Primary focus	Evidence setting	Decision	Role in synthesis
		secondary metabolites			
Nurayuda et al. (2026)	Indonesia; maize	*Chelonus formosanus* occurrence and parasitism	Field survey and laboratory rearing	Include - core	Natural-enemy discovery and local parasitism
Durocher-Granger et al. (2026)	Zambia; smallholder systems	Collective conservation biocontrol and farmer preferences	Community intervention and survey	Include - core	Adoption and institutional implementation
Peter et al. (2026)	Kenya; laboratory/screenhouse	*Coccygidium luteum* responses to maize and companion-plant volatiles	Behavioral and chemical-ecology assays	Include - core	Conservation biocontrol mechanism
Huston et al. (2026)	Australia	Two mermithid lineages parasitizing FAW	Field surveillance and molecular identification	Include – core	Natural-enemy discovery
Pec et al. (2026)	Brazil; sugarcane	Predator response to herbivore- and microbe-induced volatiles	Laboratory behavioral and chemical ecology	Include – core	Context-dependent multitrophic effects
Giacomelli et al. (2026)	Brazil; maize	Baculovirus versus synthetic insecticides on Bt and non-Bt maize	Two planting-date field trial	Include – core	Negative field evidence and delivery gap
Avellar et al. (2026)	Brazil; forage sorghum	*Melanaphis sorghi* ecology, climate, predators, and insecticide use	Two-season field ecology	Exclude	FAW incidental; no direct FAW biological-control outcome
Frimpong-Anin et al. (2026)	Ghana; maize	*Telenomus remus* integrated with fungi and nematodes	Field trials in two ecological zones	Include – core	Combined-agent field efficacy
Shi et al. (2026)	China; laboratory	Alternative host for *Meteorus pulchricornis*	Laboratory rearing and fitness	Include - enabling	Scalability of augmentative biological

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Study	Context	Primary focus	Evidence setting	Decision	Role in synthesis
		mass rearing	comparison		control
Mendez-Flota et al. (2026)	Mexico; maize	Beneficial insects under biorational insecticides	Field experiment and community sampling	Include - contextual	IPM compatibility and non-target evidence
Giri et al. (2026)	Nepal; laboratory	Egg traits affecting *Telenomus remus* and *Trichogramma chilonis*	Controlled factorial laboratory experiments	Include – core	Parasitoid performance and host-stage constraints

Parasitoid discovery, performance, and production

The parasitoid evidence ranged from field association to controlled performance and mass-rearing feasibility. In West Kalimantan, *Chelonus formosanus* emerged from 23 of 173 collected FAW larvae, producing a mean parasitism rate of 11.24%, with field-specific values from 4.76% to 20.98%. The study established local association but did not test whether this parasitism reduced crop damage or pest population growth (Nurayuda et al., 2026).

Under controlled conditions in Nepal, *Telenomus remus* consistently performed better than *Trichogramma chilonis*. Across egg densities and ages, mean parasitism was 75.83% for *T. remus* and 63.95% for *T. chilonis*. Parasitism declined from 81.67% at 20 eggs to 59.26% at 60 eggs and from 83.24% in eggs younger than 12 hours to 56.62% in eggs aged 48-60 hours. Adult emergence followed the same pattern, and *T. remus* was better able to exploit multilayered or scaled egg masses. These results show that release timing, egg age, and egg-mass architecture are central operational variables rather than minor laboratory details (Giri et al., 2026).

Parasitoid foraging may also be manipulated through habitat design. Females of *Coccygidium luteum* were significantly attracted to volatiles from FAW-damaged maize and intact sweet potato, bean, and groundnut plants, but not to intact maize or cassava. In multiple-choice assays, attractive companion plants performed similarly to damaged maize and better than the solvent control. The study identified several electrophysiologically active volatiles that could inform companion-crop selection, although the evidence remained mechanistic and did not quantify field parasitism or yield (Peter et al., 2026).

A production bottleneck was addressed by Shi et al. (2026), who evaluated *Plodia interpunctella* as an alternative host for *Meteorus pulchricornis*. Parasitoids reared on the alternative host retained parasitism, cocoon formation,

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and adult emergence rates close to those reared on FAW, although body size and fecundity were somewhat reduced. Parasitism was 48.00% on the substitute host versus 50.00% on FAW, and adult emergence was 93.33% versus 94.17%. This supports scalable rearing, but field release quality, host-searching behavior, and cost per viable parasitoid remain untested.

Entomopathogenic fungi, nematodes, and viruses

Microbial-control studies showed strong potential but divergent maturity. Senousy et al. (2026) isolated *Botryotrichum domesticum*, *Albifimbria verrucaria*, and *Purpureocillium lilacinum* from Egyptian soils. At 1×10^9 conidia mL^{-1}, cumulative larval mortality ranged from 60% to 84.44% after 14 days. *Albifimbria verrucaria* had the lowest reported LC50 and LT50, while crude metabolites caused up to 50% larval mortality. These data support agent discovery and laboratory efficacy, but not field reliability, formulation stability, or environmental safety.

Herlinda et al. (2026) moved closer to operational delivery by comparing root drench, seed treatment, and foliar inoculation with endophytic *Beauveria bassiana*. Colonization was detectable across the maize growth period but generally declined with plant age. Seed treatment produced the highest early colonization, reaching 34.29% at 28 days after planting, while larval mortality or abnormal pupation reached 33.33% in some seed-treatment observations. Overall field damage did not differ consistently among treatments, although seed-treated plants showed lower damage at one observation date. Egg parasitism was not significantly affected, suggesting compatibility with egg parasitoids.

The strongest combined-agent field evidence came from Ghana. Frimpong-Anin et al. (2026) compared *Telenomus remus* alone with combinations including *Beauveria bassiana* and *Metarhabditis rainai*. Egg parasitism remained between 43.24% and 61.53% across treatments, whereas larval mortality increased to 75.00-87.65% in combined treatments compared with 4.03-7.89% under *T. remus* alone. Combined treatments also improved yield, although ecological zone influenced parasitism, reinfestation, and crop performance. The study therefore demonstrated complementarity across pest life stages and highlighted environmental moderation of efficacy.

By contrast, Baculovirus spodoptera products did not provide satisfactory control in southern Brazilian maize trials. Giacomelli et al. (2026) found that biological treatments and untreated plots frequently retained high proportions of plants above the damage threshold, and biological treatments were associated with lower yield than the most effective synthetic options. Hybrids expressing Vip proteins performed well without additional sprays, whereas Cry-only and non-Bt hybrids required repeated intervention. This negative evidence is important because it identifies application timing, larval instar, spray penetration,

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dose, and technology as probable barriers to viral field performance.

Huston et al. (2026) identified two distinct mermithid nematode lineages parasitizing FAW in northern Australia. Molecular evidence supported separate species-level lineages, but post-parasitic juveniles could not be assigned reliably to known genera. The records expand the inventory of natural mortality factors in the invaded range, yet prevalence, host specificity, life cycle, rearing feasibility, and suppression capacity remain unknown.

Multitrophic interactions, beneficial insects, and conservation biological control

The ecological studies demonstrate that natural-enemy recruitment is conditional rather than universally enhanced by induced plant cues. Peter et al. (2026) showed attraction of *Coccygidium luteum* to several companion-plant odor blends. In contrast, Pec et al. (2026) found that *Doru luteipes* preferred clean air over volatiles from sugarcane infested by FAW, whether or not plants were inoculated with *Metarhizium robertsii*. The predator was attracted to FAW-infested maize in a positive-control assay, indicating that crop identity and volatile context changed the behavioral response. These opposing outcomes caution against transferring semiochemical strategies across crop-natural-enemy systems without validation.

Compatibility with beneficial arthropods was considered by Mendez-Flota et al. (2026). In Mexican maize, 639 beneficial insects were recorded, including 491 predators and 43 parasitoids. Spinetoram and novaluron treatments did not significantly change beneficial-insect abundance relative to the control, and observed FAW parasitism by Braconidae and Tachinidae was 13.15%. However, the study was short term, identification was largely at family level, and persistent pesticide residues were detected. It therefore provides useful contextual evidence for IPM compatibility but not proof of long-term ecological safety.

Durocher-Granger et al. (2026) extended conservation biological control from ecology to collective implementation. Farmers in two Zambian districts expressed high willingness to implement intercropping, flower strips, reduced insecticide use, and crop diversification with neighboring farmers, with reported willingness generally between 94% and 100%. Nevertheless, limited knowledge, access to seed and inputs, labor requirements, incompatibility with current practices, insufficient income, coordination, and leadership were major constraints. Only 35% reported planning pest management in advance. Thus, stated willingness alone did not establish sustained adoption. As shown in Table 2, the included studies were distributed across six evidence-to-implementation maturity levels, ranging from natural-enemy discovery and mechanistic characterization to field validation, scaling, and operational adoption. The table highlights that most studies remained concentrated at the early and intermediate stages of evidence development, whereas relatively few addressed long-term field reliability, production feasibility, economic viability, or sustained farmer adoption. Maturity levels were not treated as mutually exclusive because individual studies could contribute evidence to more than one stage of the continuum.

Table 2. Evidence-To-Implementation Maturity Levels Represented In The Included Studies And Their Principal Unresolved Issues.

Maturity level	Question answered	Representative studies	Main unresolved issue
1. Discovery/association	Is a natural enemy associated with FAW?	Nurayuda et al.; Huston et al.	Prevalence, causality, host specificity, suppression
2. Mechanism/characterization	How does the agent or ecological cue act?	Peter et al.; Pec et al.; Senousy et al.	Transferability from controlled assays to field conditions
3. Controlled efficacy	Can the agent kill or parasitize FAW under defined conditions?	Giri et al.; Senousy et al.	Dose, timing, strain quality, standardized outcomes
4. Field validation/crop protection	Does the intervention reduce damage or improve yield?	Herlinda et al.; Frimpong-Anin et al.; Giacomelli et al.	Multi-season consistency, environmental moderation, delivery
5. Scaling and production	Can the agent be produced, formulated, delivered, and afforded?	Shi et al.; Herlinda et al.	Cost, quality control, shelf life, release or application logistics
6. Operational adoption	Can farmers and institutions sustain the strategy?	Durocher-Granger et al.	Coordination, extension capacity, incentives, long-term adoption

The central gap is translation, not agent scarcity

The included literature does not suggest a shortage of candidate biological-control agents. Parasitoids, fungi, nematodes, viruses, predators, and conservation-biological-control mechanisms are represented across continents. The dominant gap is the transition from association or controlled efficacy to repeatable crop protection. Newly recorded *Chelonus formosanus* and mermithids may contribute to natural mortality, but their operational value cannot be inferred from occurrence alone. Similarly, high laboratory mortality from entomopathogenic fungi is promising but does not resolve formulation, persistence, whorl penetration, dose, or climatic sensitivity.

Combining agents can overcome stage specificity, but compatibility must be demonstrated

FAW passes through egg, larval, pupal, and adult stages that differ in exposure and susceptibility. A single agent is unlikely to control every stage consistently. The Ghana field study provides the clearest support for combining an egg parasitoid with fungal

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and nematode agents that target later stages. The stable egg-parasitism rates alongside higher larval mortality indicate functional complementarity. The endophytic *Beauveria bassiana* study also suggests that fungal seed treatment can be compatible with egg parasitism. However, compatibility should be measured directly for each agent, developmental stage, application interval, and environmental context because entomopathogens may impair parasitoids through direct exposure or altered host quality.

Biological-control efficacy is strongly context dependent

Three forms of context dependence recur. First, host traits matter: egg age, density, scale cover, and spatial arrangement influenced parasitoid performance. Second, crop and chemical context matter: companion-plant volatiles attracted *Coccygidium luteum*, whereas FAW-induced sugarcane volatiles reduced *Doru luteipes* attraction even though the predator responded positively to infested maize. Third, agronomic and environmental context matter: Ghanaian ecological zones altered parasitism, reinfestation, and yield, while Brazilian baculovirus performance depended on hybrid background, planting date, pest pressure, and likely application timing. These results argue against universal efficacy claims based on a single isolate, crop, season, or laboratory assay.

Field underperformance should be treated as design information

The Brazilian baculovirus trial is particularly valuable because it documents a plausible biological-control failure under commercial-style field pressure. Such evidence is often underrepresented in reviews that emphasize positive mortality results. Underperformance identifies testable engineering and ecological problems: virus deposition in the whorl, susceptibility of early versus late instars, ultraviolet degradation, dose, spray volume, adjuvants, and interaction with Bt traits. Future research should report the complete application chain rather than only active-agent identity.

Scaling requires biological production and social organization

Implementation readiness has at least two dimensions. The biological dimension includes mass rearing, formulation, shelf life, release density, and quality control. The alternative-host study for *Meteorus pulchricornis* addresses an important rearing constraint, but economic comparison and post-release performance remain necessary. The social dimension includes farmer knowledge, incentives, trusted leadership, extension services, and coordination across adjacent fields. Zambian farmers expressed strong willingness to cooperate, yet the barriers they reported show why positive attitudes cannot be equated with adoption. For mobile pests, conservation biological control may require landscape-level

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coordination that exceeds individual farm decision making.

Research gaps and priorities

Eight high-priority gaps emerge from the synthesis. First, field trials should be repeated across seasons, ecological zones, crop stages, and pest-pressure levels. Second, studies should use a minimum common outcome set that includes pest density, parasitism or infection, standardized plant-damage scores, marketable yield, and economic return. Third, combined-agent studies should quantify compatibility, sequence, and exposure pathways rather than assume additivity. Fourth, formulations and delivery systems should be tested for persistence, whorl penetration, ultraviolet protection, and application timing. Fifth, non-target effects should be measured at species and functional levels over longer periods. Sixth, adoption research should move from stated preference to longitudinal observation of implementation, maintenance, and cost sharing. Seventh, mass-production systems should be evaluated not only for rearing efficiency but also for their effects on agent quality, fitness, and field performance. Eighth, geographical transferability should be tested because biological-control performance may vary across crops, climates, pest populations, and farming systems. As summarized in Table 3, these research gaps reflect the need to move beyond agent discovery and short-term efficacy testing toward standardized field validation, scalable production, ecological safety, and sustained implementation. The table also links each gap to a specific research design that could strengthen the evidence base for biological control of fall armyworm.

Table 3 Major Research Gaps In Fall Armyworm Biological Control And Recommended Study Designs To Address Them.

Gap	Why current evidence is insufficient	Recommended next study
Laboratory-to-field translation	High mortality or parasitism is often measured under protected, uniform conditions.	Multi-location, multi-season field trials with standardized application and weather reporting.
Outcome heterogeneity	Mortality, parasitism, damage, and yield are not consistently measured together.	Adopt a core outcome set linking biological activity to crop and economic outcomes.
Compatibility among agents	Combined strategies may be complementary or antagonistic depending on timing and exposure.	Factorial compatibility trials with sequence, interval, and non-target endpoints.
Formulation and delivery	Field failure can result from ultraviolet exposure, poor deposition, larval concealment, or short persistence.	Engineering studies on adjuvants, encapsulation, spray technology, dose, and whorl targeting.

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Gap	Why current evidence is insufficient	Recommended next study
Mass production and quality	Alternative hosts may reduce cost but can alter parasitoid size, fecundity, and behavior.	Economic rearing trials followed by field release and quality-control benchmarks.
Ecological safety	Short-term abundance may miss sublethal and community-level effects.	Longitudinal non-target monitoring across trophic groups and seasons.
Adoption and collective action	High stated willingness does not prove sustained practice.	Longitudinal implementation research with cost sharing, leadership, extension, and compliance measures.
Geographical transferability	Agent performance varies with crop, climate, local strains, and farming systems.	Reciprocal validation of local agents and protocols across native and invaded regions.

Review Limitations

This review has five main limitations. First, the literature search was restricted to a single database and further limited to Open Access publications, English-language articles, and records classified within Agricultural and Biological Sciences. These restrictions may have excluded relevant subscription-based studies, non-English publications, and articles indexed under related subject areas, thereby introducing database, access, language, subject-area, and regional selection biases. Second, full texts were retrieved for only 13 of the 45 records that met all database filters. Of these, 12 articles were included in the final synthesis, while 32 records could not be assessed through the access routes used. Consequently, the analytical corpus may be affected by retrieval and availability bias. Third, the executed Boolean expression did not fully group the FAW concept and the biological-control concept, and wildcards were not applied to several terms. These search characteristics may have reduced retrieval precision or omitted relevant terminological variants. Fourth, the publication window was restricted to records indexed as 2026 publications and available up to 2 July 2026. The review therefore represents a recent and partial-year evidence snapshot rather than the historical development or complete 2026 literature on FAW biological control. Fifth, study selection, thematic coding, and interpretation involved reviewer judgment, as is inherent in narrative synthesis. No formal risk-of-bias or methodological-quality assessment was conducted across the included studies. Accordingly, the findings should be interpreted as a structured narrative synthesis of the retrievable portion of recent cross-regional evidence rather than as an exhaustive systematic review or meta-analysis.

D. Conclusion

The retrievable open-access records indexed as 2026 publications and available up to 2 July 2026 indicate active research

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on the biological control of fall armyworm across Africa, Asia, the Americas, and Oceania. However, the evidence remains unevenly distributed along the pathway from agent discovery to operational implementation. Parasitoids and entomopathogens frequently demonstrated promising efficacy under controlled conditions, while a limited number of field studies showed that compatible combinations of biological agents may reduce pest damage and improve crop-level outcomes. Conservation biological-control approaches also showed potential to influence natural-enemy behavior and attract farmer interest, although their effectiveness was strongly dependent on crop identity, ecological context, and implementation conditions. The reviewed evidence also demonstrates that promising laboratory or mechanistic findings do not necessarily translate into reliable field control. Baculovirus-based interventions may underperform under certain field conditions, plant-volatile effects may differ among crop–natural-enemy systems, and newly recorded natural enemies often lack evidence of population suppression, crop protection, or economic benefit. Future research should therefore move beyond the continued identification of candidate agents and prioritize multi-season field validation, formulation and delivery, compatibility among agents, standardized crop and economic outcomes, ecological safety, quality assurance in mass production and sustained farmer adoption. The evidence-to-implementation continuum proposed in this review offers a structured framework for distinguishing biological associations and experimental efficacy from field-validated and operationally scalable biological-control strategies. Within its defined search scope, this review provides a timely cross-regional snapshot of emerging evidence, translational barriers, and implementation priorities in fall armyworm biological control.

E. References

Avellar, G. S., Marriel, I. E., Santos, N. M., Ferreira, A. V., Santos, D. G., & Mendes, S. M. (2026). Ecological dynamics of *Melanaphis sorghi* in forage sorghum: Effects of climate, predators, and insecticide use. Revista Brasileira de Entomologia, 70(1), e20250036. https://doi.org/10.1590/1806-9665-RBENT-2025-0036

Durocher-Granger, L., Rware, H., Mudenda, S. K., Chiboola, M. M., Ludwig, D., & Leeuwis, C. (2026). Awareness and community preferences on collective pest management for fall armyworm in rural Zambia. NJAS: Impact in Agricultural and Life Sciences, 98(1), 2627092. https://doi.org/10.1080/27685241.2026.2627092

Frimpong-Anin, K., Amoabeng, B. W., Asamoah, J. F., Danso, Y., Ohene-Mensah, G., Awarikabey, E. N., Appiah, D. A., Antwi, D., Kwodane, M., Abugri, B., & Gyamfi, M. (2026). Integration of egg parasitoids and entomopathogens for the management of fall armyworm *Spodoptera frugiperda* on maize in Ghana. Academia Biology, 4. https://doi.org/10.20935/AcadBiol8193

Giacomelli, T., Schardong, I. S., Pozebon, H., Perini, C. R., Camatti, G., Brum, E. M., Arnemann, J. A., & Guedes, J. V. C. (2026). Synthetic or biological insecticide performance on Bt corn to control *Spodoptera frugiperda*. International Journal of Tropical Insect Science, 46, 409-418. https://doi.org/10.1007/s42690-025-01691-5

Giri, K., Pokhrel, M. R., & Bhandari, G. (2026). Influence of egg traits on parasitism by *Trichogramma chilonis* and *Telenomus remus* against *Spodoptera frugiperda*. Frontiers in Insect Science, 6, 1749736. https://doi.org/10.3389/finsc.2026.1749736

Herlinda, S., Saripudin, S., Thosin, T., Madya, S. P., Sari, J. M. P., Suwandi, S., Anggraini, E., & Suharjo, R. (2026). Endophytic *Beauveria bassiana* in root, seed, and foliar-treated maize affecting *Spodoptera frugiperda* larvae and its parasitization eggs. Journal of Tropical Plant Pests and Diseases, 26(1), 59-67. https://doi.org/10.23960/j.hptt.12659-67

Huston, D. C., Caglar, C., Bonney, S., Bond, S. J., Ratnayake, W., Thistleton, B., Tadle, F. P. J., Subramaniam, S., & Hodda, M. (2026). Two unknown species of Mermithidae parasitising fall armyworm *Spodoptera frugiperda* in Australia. Australasian Plant Pathology, 55, 20. https://doi.org/10.1007/s13313-026-01108-y

Mendez-Flota, D. L., Gonzalez-Moreno, A., Ruiz-Sanchez, E., & Flota-Banuelos, C. (2026). Beneficial insects in maize crops: Response to the use of biorational insecticides for the control of *Spodoptera frugiperda*. Tropical and Subtropical Agroecosystems, 29, Article 018. https://doi.org/10.56369/tsaes.6587

Nurayuda, N., Kustiati, K., Saputra, F., & Wardoyo, E. R. P. (2026). Parasitoid *Chelonus formosanus* and its parasitization level of *Spodoptera frugiperda* in corn plantations in Rasau Jaya, West Kalimantan. Jurnal Entomologi Indonesia, 23(1), 76-82. https://doi.org/10.5994/jei.23.1.76

Pec, M., Salazar-Mendoza, P., Azevedo, K. E. X., Magalhaes, D. M., Delalibera, I., Jr., & Bento, J. M. S. (2026). When calls for help backfire: Induced plant volatiles reduce the attraction of a nocturnal predator in sugarcane. Journal of Chemical Ecology, 52, 7. https://doi.org/10.1007/s10886-025-01682-3

Peter, E., Subramanian, S., Yusuf, A., Mohamed, S. A., Torto, B., Martin, E. A., & Tamiru, A. (2026). Behavioral and electrophysiological responses of fall armyworm larval parasitoid *Coccygidium luteum* to maize and companion plant volatiles. BioControl, 71, 295-308. https://doi.org/10.1007/s10526-025-10377-3

Senousy, F. A., El Arnaouty, S. A., Kortam, M. N., Ismail, I. M., Awad, M., & Zayton, M. A. (2026). Isolation, identification, and pathogenicity of entomopathogenic fungal strains and their secondary metabolites against *Spodoptera frugiperda*. Neotropical Entomology, 55, 11. https://doi.org/10.1007/s13744-026-01360-3

Shi, R., Lu, J., Shi, A., Shu, X., Yang, L., Wang, P., Yan, Y., Li, Z., Wu, Q., Wang, Z., Ye, X., Chen, X., & Tang, P. (2026). *Plodia interpunctella* as the suitable alternative host for mass rearing of *Meteorus pulchricornis*. Egyptian Journal of Biological Pest Control, 36, 16. https://doi.org/10.1186/s41938-026-00898-z