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Bioecology, invasion dynamics, and integrated management strategies of the fall armyworm: A comprehensive review

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Abstract
The Fall Armyworm (FAW), *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae), is a destructive, invasive, and highly polyphagous insect pest native to tropical and subtropical regions of the Americas. Outside its native range, FAW was first reported in Africa in 2016, from where it underwent rapid expansion across Asia, arriving in India in May 2018 (Karnataka) and subsequently spreading to Himachal Pradesh during the Kharif season of 2020. FAW presents a severe biosecurity threat to global food security, causing yield losses in maize ranging from 20% to 50% globally, 36% to 40% in India, and infestation levels up to 47.29% in early outbreaks in Himachal Pradesh. Its exceptional invasion success is driven by a broad host range (>300 species), high fecundity (900–1000 eggs/female), short generation cycle (24–40 days), strong migratory flight capability, absence of true diapause, and genetic plasticity represented by its Corn (C) and Rice (R) strains. This review paper provides a thorough, comprehensive synthesis of FAW bioecology, host preferences, developmental biology, climate drivers, and historical invasion dynamics, detailing its continuous year-round expansion across Indian cropping cycles. Furthermore, we critically review Integrated Pest Management (IPM) tactics encompassing systematic scouting (FAMEWS), push-pull habitat manipulation, mechanical practices (sand/soil whorl application), native biological control agents (predators, parasitoids, entomopathogenic fungi, bacteria, viruses, and nematodes), botanical extracts (azadirachtin, Annona squamosa, Agave americana), and CIBRC-approved chemical insecticides with IRAC mode-of-action rotation. Finally, recent molecular and precision advances—including RNA interference (RNAi), CRISPR/Cas9 genome editing, nano-silicon defence priming, and AI-driven forecasting—are evaluated to chart a sustainable path for long-term FAW suppression.

Keywords: Spodoptera frugiperda, Fall Armyworm, Bioecology, Invasion Dynamics, Integrated Pest Management, Push-Pull Strategy, Biological Control, Insecticide Resistance

Introduction
The Fall Armyworm (FAW), *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae), is a highly destructive, alien invasive, and polyphagous insect pest that has emerged as a major constraint to sustainable maize production and agricultural biosecurity globally (Goergen *et al*. 2016; Sharanabasappa *et al*. 2018) [12, 30]. Native to the tropical and subtropical regions of the Americas, FAW has long been recognized as a primary agricultural pest causing substantial economic losses in maize, sorghum, rice, and cotton across North, Central, and South America (Wan *et al*. 2021) [35]. Its invasive expansion outside its native distribution began with its initial detection in West and Central Africa in early 2016 (Goergen *et al*. 2016) [12]. Driven by exceptional adult flight capabilities and trade-facilitated movement, the pest swept across sub-Saharan Africa in less than two years before invading the Asian continent.

In India, the first confirmed field infestation of *S. frugiperda* was documented in May 2018 on maize crops in Shivamogga, Karnataka (Sharanabasappa *et al*. 2018) [30]. Following its initial establishment, FAW displayed extraordinary spatial dispersal, colonizing nearly all major Indian maize-growing states within twelve months (Suby *et al*. 2020; Borgohain *et al*. 2024) [6, 34]. In Himachal Pradesh, FAW was first officially recorded on maize during the Kharif season of 2020 (Ankita *et al*. 2020) [3], subsequently establishing breeding populations across multiple mid-hill and lower-hill districts (Sharma 2021) [32].

The economic impact of *S. frugiperda* is immense. On a global scale, maize yield reductions associated with unmanaged FAW infestations range from 20% to 50%, with catastrophic crop failure exceeding 70% under high pest pressure (Lhamine *et al*. 2026) [19]. In India, yield losses in heavily infested maize fields are routinely reported between 36% and 40% (Sharanabasappa *et al*. 2018; Suby *et al*. 2020) [30, 34]. The pest's high economic severity stems from a combination of aggressive feeding habits, rapid developmental rate, high reproductive potential, strong dispersal capability, and ecological resilience. Importantly, the cryptic feeding behavior of larvae—which remain concealed deep inside the plant whorl or developing ears—presents a formidable management challenge, rendering conventional contact sprays largely ineffective. Consequently, long-term management cannot rely on single-tactic chemical interventions; rather, a holistic Integrated Pest Management (IPM) framework combining monitoring, cultural, mechanical, biological, botanical, and rational chemical measures is required.

Taxonomic Position and Host Strains
Taxonomically, the fall armyworm belongs to the Kingdom Animalia, Phylum Arthropoda, Class Insecta, Order Lepidoptera, Superfamily Noctuoidea, and Family Noctuidae. The species was originally described as *Phalaena frugiperda* by J.E. Smith in 1797 and subsequently placed under the genus Spodoptera Guenée. The genus *Spodoptera* encompasses several major crop

pests, including Spodoptera litura (Fabricius), Spodoptera exigua (Hübner), and Spodoptera mauritia (Boisduval). Accurate diagnostic identification of *S. frugiperda* is critical because sympatric noctuid species frequently co-occur in maize and grass ecosystems, producing overlapping leaf feeding damage (Sharanabasappa *et al*. 2018) [30].

Host Strain Diversity: A defining biological feature of *S. frugiperda* is the presence of two sympatric, morphologically identical but genetically distinct host-associated strains (Wan *et al*. 2021; Yainna *et al*. 2022) [35, 36]:

Corn Strain (C-strain): Primarily infests maize (*Zea mays*), sorghum (*Sorghum bicolor*), cotton (*Gossypium hirsutum*), and sugarcane (*Saccharum officinarum*). The C-strain is highly dominant in major maize-producing ecosystems worldwide and represents the primary strain invading Africa and Asia (Suby *et al*. 2020; Wan *et al*. 2021) [34, 35].

Rice Strain (R-strain): Preferentially targets rice (*Oryza sativa*), pasture grasses (e.g., Cynodon dactylon), and wild turf grasses. While host fidelity is strong in native populations, inter-strain hybridization occurs in field settings, conferring enhanced ecological flexibility and host adaptability during geographic range expansion (Yainna *et al*. 2022) [36].

Current Scenario of FAW Infestation

1. Global Scenario

Since its initial detection in West Africa in 2016 (Goergen *et al*. 2016) [12], *S. frugiperda* has established itself as one of the most prolific transboundary agricultural invaders of the 21st century. According to official reports from the Food and Agriculture Organization (FAO), FAW has spread to more than 80 countries across Africa, Asia, Australia, and the Pacific Islands (FAO 2026) [11]. In sub-Saharan Africa alone, annual economic losses in maize production attributed to FAW have been estimated between US$ 2.4 billion and US$ 6.2 billion, directly threatening the food security and livelihoods of millions of smallholder farming households (Lhamine *et al*. 2026) [19].

2. Situation in India

Following its initial discovery in Shivamogga, Karnataka in May 2018 (Sharanabasappa *et al*. 2018) [30], FAW demonstrated rapid range expansion across the Indian subcontinent. By late 2018 and early 2019, severe infestations were confirmed in southern, central, western, and eastern states, including Andhra Pradesh, Telangana, Tamil Nadu, Maharashtra, Odisha, Gujarat, Chhattisgarh, Madhya Pradesh, Rajasthan, and Bihar (Suby *et al*. 2020; Borgohain *et al*. 2024) [6, 34]. The rapid colonization was favored by India's diverse agro-climatic zones and continuous, overlapping maize cultivation practices across Kharif, Rabi, and summer cropping seasons.

3. Situation in Himachal Pradesh

In Himachal Pradesh, *S. frugiperda* was first recorded on Kharif maize in 2020 (Ankita *et al*. 2020) [3]. Subsequent systematic field surveillance confirmed its establishment across major maize-growing districts, including Una, Kangra, Hamirpur, Chamba, Mandi, and Solan (Sharma 2021) [32]. Early outbreak surveys recorded peak plant damage levels reaching up to 47.29% in highly susceptible fields. District-wise monitoring conducted during 2022 documented mean infestation rates of approximately 15% in Una, 15–20% in Solan, 10–12% in Hamirpur, 12% in Kangra, 10% in Chamba, and 8–10% in Mandi (Sharma 2021) [32]. These figures emphasize that FAW has successfully adapted to the mid-hill agro-climatic conditions of Himachal Pradesh, necessitating continuous monitoring and localized IPM strategies.

Host Range, Feeding Behaviour and Damaging Symptoms

Host Plant Hierarchy: S. frugiperda is an extraordinarily polyphagous species, with documented feeding records on more than 350 plant species belonging to 76 botanical families (Wan *et al*. 2021) [35]. Despite its wide host breadth, the pest displays a clear preference for members of the family Poaceae. In Indian agricultural landscapes, host plant preference hierarchy is categorized as follows (Mallapur *et al*. 2021; Savadatti *et al*. 2024) [21]:

- **Primary Hosts:** Maize (*Zea mays*), Hybrid Sorghum (*Sorghum bicolor*), and Fodder Sorghum.
- **Secondary Hosts:** Pearl Millet / Bajra (*Pennisetum glaucum*), Sugarcane (*Saccharum officinarum*), Wheat (*Triticum aestivum*), Cotton (*Gossypium hirsutum*), and Napier Grass (*Pennisetum purpureum*).
- **Alternate / Weed Hosts:** Bermuda Grass (*Cynodon dactylon*), Brachiaria spp., *Echinochloa spp.*, *Amaranthus spp*., and *Digitaria spp.* (Mallapur *et al*. 2021) [21]. Weed hosts play a vital ecological role by functioning as green bridges and population reservoirs between primary cropping seasons.

Feeding Behavior and Damage Progression: The damaging stage is restricted to the larval instars, which exhibit distinct stage-specific feeding behaviors (FAO 2020; Suby *et al*. 2020) [10, 34]:

1. **Early Instars (1st–2nd):** Newly hatched larvae feed gregariously on the underside of young leaves, scraping the epidermal layer while leaving the upper cuticle intact. This results in semi-transparent, papery patches on the foliage, standardly termed 'window-pane' damage.
2. **Mid-to-Late Instars (3rd–6th):** As larvae mature, their voracious feeding produces extensive ragged, irregular holes across expanding leaves. Concurrently, larvae excrete copious quantities of dark, moist, sawdust-like frass that accumulates within the whorl, blocking light and promoting fungal decay.
3. **Reproductive Stage Feeding:** During reproductive crop growth, larvae bore into emerging tassels and developing ears. Direct kernel consumption reduces grain quantity.
4. **Biology and Life Cycle**

   Spodoptera frugiperda undergoes complete holometabolous metamorphosis involving four distinct developmental stages: egg, larva, pupa, and adult. The total life cycle duration ranges from 24 to 40 days under optimal thermal conditions (25–30°C), allowing 10 to 12 overlapping generations per year in tropical regions (Pathak *et al*. 2024) [25]. Under Indian laboratory and field conditions, developmental stage durations are structured as follows:

1. Egg Stage

Eggs are dome-shaped, measuring 0.4 mm in diameter and 0.3 mm in height. Females deposit eggs in masses containing 100 to 200 eggs, typically on the underside of leaves or inner whorl structures. Egg masses are covered with a protective layer of pinkish-grey scales detached from the female's abdomen, shielding them from desiccation and micro-parasitoids. Individual females exhibit immense fecundity, laying between 900 and 1,000 eggs over their lifespan, with laboratory maxima exceeding 1,200 eggs. The incubation period is short, lasting 2 to 3 days under warm conditions (Pathak *et al*. 2024) [25].

2. Larval Stage

Key Diagnostic Features of Mature Larvae: The larval development encompasses six distinct instars over a duration of 14 to 19 days (Pathak *et al*. 2024) [25]. First-instar larvae are light green with dark head capsules. As larvae mature through subsequent instars, body coloration varies from brownish-green to dark brown or charcoal black. Diagnostic morphological characteristics for field identification include:

Head Capsule: A prominent, raised white inverted 'Y' mark on the frontoclypeal area of the dark head capsule.

8th Abdominal Segment: Four dark, elevated pinacula arranged in a precise square pattern on the dorsal surface of the eighth abdominal segment.

Body Markings: Trapezoidally arranged dark spots on other abdominal segments, flanked by three pale longitudinal stripes running along the length of the body.

3. Pre-Pupal and Pupal Stages

Upon completing the sixth instar, mature larvae cease feeding, abandon the plant whorl, and burrow into the top 2–8 cm of soil. They undergo a sluggish pre-pupal phase lasting 1 to 3 days, construct a loose silk cocoon binding soil particles, and transform into pupae. Pupation can also occur within the leaf whorl or ear husks if soil entry is impeded. The pupa is smooth, obtect, initially reddish-brown, and measures 13 to 17 mm in length. The pupal duration lasts 6 to 9 days under warm ambient conditions (Pathak *et al*. 2024) [25].

4. Adult Stage

Sexual Dimorphism: Adults are nocturnal moths with a wingspan of 32 to 40 mm. Sexual dimorphism is highly pronounced in forewing coloration and patterning (Pathak *et al*. 2024) [25]:

Male Adults: Forewings are shaded greyish-brown, featuring a distinct light-brown oval spot near the center and a prominent triangular white patch near the apical margin.

Female Adults: Forewings are less distinctly marked, displaying uniform mottled greyish-brown coloration.

In both sexes, hindwings are iridescent silvery-white with a narrow dark border along the outer margin. Adults are strong nocturnal flyers, living for 9 to 14 days, during which mating and long-distance migration occur.

Environmental Drivers and Correlation with FAW Infestation

Abiotic environmental factors—primarily ambient temperature, relative humidity, and rainfall—exert a profound influence on the phenology, survival, reproduction, and population dynamics of *S. frugiperda* (Raman *et al*. 2024) [27]. Understanding these environmental drivers is essential for building predictive population models and timing management interventions.

Temperature and Humidity Dynamics: The optimal thermal threshold for FAW development spans 25°C to 30°C, coupled with relative humidity levels of 60% to 80%. Within this thermal band, developmental kinetics accelerate, shortening generation times and leading to rapid population build-up and generation overlap (Pathak *et al*. 2024; Raman *et al*. 2024) [25, 27]. Temperatures exceeding 35°C reduce egg viability and adult longevity, whereas extreme cold (<10°C) arrests development, as FAW lacks a diapause mechanism.

Precipitation Effects: Rainfall demonstrates a dual ecological impact. Moderate, well-distributed rainfall maintains host plant vigor and microclimatic humidity, supporting population expansion. Conversely, intense rainfall events act as a physical mortality agent, dislodging egg masses and young 1st–2nd instar larvae from leaf surfaces and drowning them in flooded whorls (Raman *et al*. 2024) [27].

Invasion Dynamics of Fall Armyworm

The invasion process of *S. frugiperda* follows a structured ecological progression: arrival of founder populations, establishment in suitable host landscapes, a brief lag phase, and explosive range expansion (Yainna *et al*. 2022) [36]. The pest's rapid spread across Africa and Asia represents an unprecedented case study in biological invasion dynamics.

In India, the invasion trajectory was uniquely driven by host availability and seasonal cropping patterns. Following its initial detection in Karnataka during May 2018 (Kharif season), FAW completed its reproductive cycle on rainy-season maize. As Kharif crops matured, adult moths undertook long-distance flights toward eastern and central states—including Bihar, Odisha, and West Bengal—where Rabi maize is extensively cultivated during winter. Subsequently, populations migrated toward northeastern states, where maize is grown during spring and early summer under rainfed conditions (Suby *et al*. 2020; Borgohain *et al*. 2024) [6, 34]. Because maize or alternative graminaceous hosts are present year-round across overlapping agro-ecological zones in India, S. frugiperda established permanent, continuous breeding populations across the country within a single year (Suby *et al*. 2020) [34].

Biological Traits Involved in Invasion Success

Key Biological Drivers: The extraordinary invasive capability of *S. frugiperda* is underpinned by a constellation of key biological and ecological attributes (Wan *et al*. 2021; Yainna *et al*. 2022) [35, 36]:

1. **Exceptional Fecundity:** A single female produces up to 1,000 eggs, driving rapid population growth under favorable conditions.

2. **Short Generation Time:** Completion of life cycles in 24–40 days enables 10–12 generations annually, allowing rapid population recovery following control-induced mortality.

3. **Strong Migratory Flight Capacity:** Adult moths are capable of flying up to 100 km in a single night and over 500 km during multi-day migratory movements, utilizing prevailing wind currents for long-distance transport.

4. **Extreme Polyphagy:** Ability to feed on over 350 host species ensures population survival on alternative crops and weeds during host-free periods.

5. **Absence of True Diapause:** Continuous year-round breeding in tropical and subtropical climates without compulsory diapause.

Integrated Management Strategies for FAW

Due to the pest's high reproductive capacity, cryptic whorl-feeding behavior, and rapid resistance development, reliance on single control tactics- especially routine chemical calendar spraying- is unsustainable. Effective suppression requires a multi-tiered Integrated Pest Management (IPM) framework combining surveillance, cultural practices, mechanical measures, biological control, botanical pesticides, and rational chemical interventions (Anonymous.2019; FAO 2020) [4, 10].

Monitoring and Scouting

Surveillance Protocols: Early detection forms the cornerstone of effective IPM. Monitoring should commence immediately after seedling emergence and continue through harvest.

Pheromone Traps: Install lure-baited funnel or bucket traps at a density of 5 traps/acre (12 traps/ha) at crop canopy height to track adult moth activity and trigger field scouting (Anonymous.2019) [4].

Field Scouting & Economic Thresholds: Systematic field scouting should follow a 'W' sampling pattern across the field in young crops, inspecting 20 consecutive plants at 5 random locations. Action thresholds are set at 5% damaged plants during seedling stage (1–3 weeks after emergence), 10% damaged plants during mid-whorl stage (4–7 weeks), and >10% damage during late whorl/tasseling stages (Anonymous.2019; FAO 2020) [4, 10].

Digital Surveillance: Mobile digital platforms, such as FAO's Fall Armyworm Monitoring and Early Warning System (FAMEWS), facilitate real-time mapping, rapid data sharing, and regional risk assessment (FAO 2020) [10].

Mechanical and Physical Management

Mass Trapping: Deploy 15 pheromone traps/acre to achieve mass trapping of male moths and reduce mating success (Anonymous.2019) [4].

Hand Collection: In smallholder plots, manual collection and destruction of egg masses and early-instar larval clusters provide eco-friendly early suppression.

Sand/Soil Application: Whorl Application of Sand/Soil: Applying dry sand or a dry sand + soil mixture (9:1 ratio) directly into plant whorls 30 days after sowing physically disrupts the microenvironment, suffocating and abrading larvae concealed within (Anonymous.2019) [4].

Cultural Management

Deep Summer Ploughing: Exposes soil-dwelling pupae to predatory birds, ants, solar heating, and mechanical destruction (Ministry of Agriculture 2019).

Synchronized Sowing: Synchronized planting across farming communities prevents continuous host availability and disrupts population buildup.

Intercropping: Intercropping maize with pulses (e.g., cowpea, pigeonpea, blackgram) increases floral biodiversity, provides shelter for natural enemies, and reduces pest density.

Push-Pull Technology: Push-Pull Technology: Developed by ICIPE, this habitat manipulation strategy integrates repellent intercrops ('push') with attractive border trap crops ('pull'). Desmodium (Desmodium uncinatum) is intercropped between maize rows to release volatile terpenoids (e.g., (E)-β-ocimene) that repel ovipositing FAW moths, while border plantings of Napier grass (Pennisetum purpureum) release attractive volatiles that draw moths away from maize (Dhabhai *et al*. 2025) [9].

Biological Control

Biological control represents a critical component of sustainable FAW management, utilizing natural enemies to suppress pest populations naturally or through augmentative releases.

1. Predators

A diverse complex of predatory insects attacks FAW egg masses and larvae in Indian agricultural ecosystems. Key predatory species and their target stages are summarized in Table 1.

Table 1: Predatory insect complex attacking *Spodoptera frugiperda* in India

Common Name	Scientific Name	Order: Family	References
Eight-spotted ladybird	*Harmonia octomaculata*	Coleoptera: Coccinellidae	Sharanabasappa *et al*. 2019
Transverse ladybird	*Coccinella transversalis*	Coleoptera: Coccinellidae	Sharanabasappa *et al*. 2019
Predatory stink bug	*Eocanthecona furcellata*	Hemiptera: Pentatomidae	Keerthi *et al*. 2020
Earwig	*Forficula spp.*	Dermaptera: Forficulidae	Shylesha *et al*. 2018
Assassin bug	*Rhynocoris marginatus*	Hemiptera: Reduviidae	Pradeep *et al*. 2022
Rove beetle	*Paederus fuscipes*	Coleoptera: Staphylinidae	Maruthadurai *et al*. 2024
Six-spotted ladybird	*Cheilomenes sexmaculata*	Coleoptera: Coccinellidae	Maruthadurai *et al*. 2024
Ground beetle	Carabid beetle	Coleoptera: Carabidae	Maruthadurai *et al*. 2024

Predatory wasp	Predatory wasp	Hymenoptera: Vespidae	Maruthadurai *et al*. 2024
Lynx spider	*Oxyopes birmanicus*	Araneae: Oxyopidae	Maruthadurai *et al*. 2024
Assassin bug	*Coranus siva*	Hemiptera: Reduviidae	Bhagyasree *et al*. 2025

2. Parasitoids

Hymenopteran and dipteran parasitoids provide substantial naturally occurring mortality across egg, larval, and pupal stages of FAW in India (Table 2).

Table 2: Parasitoids complex attacking *Spodoptera frugiperda* in India

Parasitoid species	Family: Order	Type	Reference
Campoletis chlorideae	Ichneumonidae: Hymenoptera	Larval endoparasitoid	Shylesha *et al*. 2018; Sharanabasappa *et al*. 2019
Coccygidium transcaspicum	Braconidae: Hymenoptera	Larval endoparasitoid	Shylesha *et al*. 2018; Gupta *et al*. 2020
Coccygidium melleum	Braconidae: Hymenoptera	Larval endoparasitoid	Sharanabasappa *et al*. 2019
Chelonus formosanus	Braconidae: Hymenoptera	Egg-larval parasitoid	Gupta *et al*. 2020; Keerthi *et al*. 2023
Eriborus sp.	Ichneumonidae: Hymenoptera	Larval parasitoid	Sharanabasappa *et al*. 2019
Odontepyris sp.	Bethylidae: Hymenoptera	Larval ectoparasitoid	Sharanabasappa *et al*. 2019
Exorista sorbillans	Tachinidae: Diptera	Larval-pupal parasitoid	Sharanabasappa *et al*. 2019
Bracon hebetor	Braconidae: Hymenoptera	Larval ectoparasitoid	Latha *et al*. 2019
Cotesia ruficrus	Braconidae: Hymenoptera	Larval endoparasitoid	Gupta *et al*. 2020; Pal *et al*. 2024

3. Entomopathogenic Fungi

Entomopathogenic fungi (EPF) penetrate insect cuticles through enzymatic hydrolysis (chitinases, proteases) and proliferate within the hemolymph, causing white or green muscardine disease. List of entomopathogenic fungi against FAW is give in (Table 3).

Table 3: Entomopathogenic fungi (EPF) species evaluated against *Spodoptera frugiperda*

Entomopathogenic fungus	Status against FAW	Reference
Beauveria bassiana (ICAR-NBAIR Bb-45, Bb-11)	Highly effective	Ramanujam *et al*. 2020
Metarhizium anisopliae (ICAR-NBAIR Ma-35)	Highly effective	Ramanujam *et al*. 2020; Bateman *et al*. 2020
Metarhizium rileyi (*Nomuraea rileyi*)	Highly effective	Shylesha *et al*. 2018; Ramanujam *et al*. 2020
Beauveria felina	Emerging	Ramanujam *et al*. 2021

4. Entomopathogenic Bacteria

Bacillus thuringiensis (Bt) is the premier bacterial bio-pesticide active against lepidopteran pests. Upon ingestion, Bt delta-endotoxins (Cry and Vip proteins) are solubilized in the alkaline larval midgut, processed by midgut proteases, and bound to specific cadherin-like receptors. This creates lytic pores in midgut epithelial membranes, causing septicemia and larval death (Polanczyk *et al*. 2000; Abbas *et al*. 2022) [1, 26]. *Bt var. aizawai* exhibits superior insecticidal potency against *S. frugiperda* compared to *Bt var. kurstaki* due to the presence of Cry1C and Cry1D toxins (Polanczyk *et al*. 2000) [26].

5. Entomopathogenic Viruses

Baculoviruses, particularly *Spodoptera frugiperda* multiple nucleopolyhedrovirus (SfMNPV), represent highly host-specific viral bio-pesticides (Hussain *et al*. 2021) [14]. SfMNPV infects midgut cells, spreading systemically and causing larval liquefaction. Co-infection with *Spodoptera frugiperda granulovirus* (SfGV) or cross-infective *Spodoptera littoralis NPV* (SpliNPV) produces synergistic mortality, offering excellent potential for bio-pesticide formulation (Bateman *et al*. 2020; Hussain *et al*. 2021) [14].

6. Entomopathogenic Nematodes

Infective juveniles (IJs) enter larvae through natural openings or thin cuticles, releasing symbiotic bacteria that induce lethal septicemia within 24 to 48 hours (Abbas *et al*. 2022; Patil *et al*. 2022; Ratnakala *et al*. 2023) [1, 24, 29].

Table 4: Entomopathogenic nematode (EPN) species evaluated against *Spodoptera frugiperda*

EPN Species	Symbiotic Bacterium	Reference
Steinernema carpocapsae	*Xenorhabdus nematophila*	Abbas *et al*. 2022; Patil *et al*. 2022
Heterorhabditis indica	*Photorhabdus luminescens*	Ratnakala *et al*. 2023
Steinernema feltiae	*Xenorhabdus bovienii*	Acharya *et al*. 2020
Steinernema riobrave	*Xenorhabdus spp.*	Abbas *et al*. 2022
Heterorhabditis bacteriophora	Photorhabdus luminescens	Acharya *et al*. 2020; Abbas *et al*. 2022
Steinernema arenarium	Xenorhabdus spp.	Acharya *et al*. 2020

Insecticide Active Ingredient	**Formulation**	**CIBRC Approved Dose**
Chlorantraniliprole + Lambda-cyhalothrin	9.3% + 4.6% ZC	35 g a.i./ha
Chlorantraniliprole + Fipronil + Emamectin benzoate	0.45% + 0.50% + 0.18% GR	48.75 + 37.5 + 15 g a.i./ha
Cyantraniliprole + Thiamethoxam	19.8% + 19.8% FS	2.38 g a.i./kg seed
Spinetoram	11.7% SC	30 g a.i./ha

Chlorantraniliprole	18.5% SC	40 g a.i./ha
Tetraniliprole	18.18% SC	50 g a.i./ha
Novaluron + Emamectin benzoate	5.25% + 0.9% SC	78.75 + 13.5 g a.i./ha

6. Botanical Control

Botanical insecticides derived from plant secondary metabolites offer eco-friendly, biodegradable alternatives to synthetic chemicals (Kavitha and Shanthi 2024; Chawanda *et al*. 2023) [7, 15].

Table 5: Efficacy and physiological modes of action of botanical extracts against *Spodoptera frugiperda*

Botanical Source	Active Compound	Reference
Neem (*Azadirachta indica)*	Azadirachtin	Kavitha and Shanthi 2024
Agave (*Agave americana)*	Saponins & Phenolics	Kavitha and Shanthi 2024
Custard Apple (*Annona squamosa*)	Acetogenins (Rolliniastatin-2)	Kavitha and Shanthi 2024
Ginger (*Zingiber officinale)*	Gingerols & Shogaols	Kavitha and Shanthi 2024
Lantana *(Lantana camara)*	Triterpenoids & Phenolics	Kavitha and Shanthi 2024
Tobacco *(Nicotiana tabacum)*	Nicotine	Chawanda *et al*. 2023
Lemongrass *(Cymbopogon citratus)*	Citral	Chawanda *et al*. 2023

Chemical Control

When FAW populations exceed economic threshold levels (5% whorl damage in young crops; 10% in mid-whorl stage), targeted chemical applications directed into the plant whorl are necessary (Ministry of Agriculture 2019). The Central Insecticide Board and Registration Committee (CIBRC), Government of India, has approved specific chemical insecticides and combinations for FAW management in maize (Table 5).

Challenges in FAW Management

The sustainable management of S. frugiperda is complicated by several interconnected physiological, behavioral, and operational challenges:

1. **Insecticide Resistance Development:** Insecticide resistance is the most alarming challenge. In its native Americas, *S. frugiperda* developed field resistance to organophosphates, carbamates, synthetic pyrethroids, Bt proteins (Cry1Fa), and spinosads.

2. **Extreme Polyphagy and Host Bridges:** Ability to complete development on over 350 host species enables FAW to persist indefinitely in wild grasses, weeds, and horticultural crops during non-maize growing periods.

3. **Cryptic Whorl Feeding Behavior**
4. **High Migratory Mobility and Continuous Re-infestation**
5. **Climate Variability:** Fluctuating thermal regimes accelerate developmental rates and unpredictably alter outbreak timing, outpacing fixed calendar management schedules.

Recent Advances and Future Prospects

To overcome management challenges and build long-term resistance management programs, advanced biotechnological and precision-agriculture strategies are being aggressively developed:

1. **RNA Interference (RNAi):** Exogenous or transgenic delivery of double-stranded RNA (dsRNA) targeting essential larval genes—such as SfCOPIα, SfCOPIβ (coatomer complex subunit genes), and SfGSTU1 (glutathione S-transferase)—induces gene silencing, causing high larval mortality, developmental arrest, and reduced fecundity without non-target toxicity.

2. **CRISPR/Cas9 Genome Editing:** CRISPR/Cas9 gene editing is used to functionalize genes involved in insecticide resistance, chemoreception, and reproductive physiology. Gene-editing tools accelerate the identification of novel target sites and support future deployment of Sterile Insect Technique (SIT) or gene-drive systems for population suppression.

3. **Nano-enabled Plant Defence Priming:** Soil or foliar application of nano-silicon formulation primes intrinsic plant defence pathways in maize. Silicification of leaf tissues physically abrades insect mandibles, while bio-chemical priming elevates defence enzymes (peroxidase, polyphenol oxidase) and induces volatile emission, attracting natural predators.

Conclusion

The fall armyworm, *Spodoptera frugiperda*, represents an unprecedented global threat to maize production, food security, and rural livelihoods. Its extraordinary invasive capability-driven by polyphagy, high reproductive output, rapid generation turnover, strong flight capacity, and absence of diapause-enabled its establishment across India and Himachal Pradesh within two years of its Asian introduction. Effective management cannot rely on sole chemical tactics. A bio-intensive Integrated Pest Management (IPM) approach-grounded in pheromone surveillance, push-pull habitat manipulation, mechanical sand whorl placement, conservation of natural predators and parasitoids (e.g., Telenomus remus, *Trichogramma chilonis*, *Rhynocoris marginatus*), utilization of biopesticides (*Metarhizium anisopliae, Bt, SfMNPV*), and IRAC-guided chemical rotation-is imperative. Future management will increasingly harness molecular innovations (RNAi, CRISPR/Cas9), nanotechnology, and AI-driven precision forecasting to ensure sustainable, long-term FAW suppression

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