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Occurrences and Bio-Control Potential of Natural Enemies of Fall Army Worm, *Spodoptera Frugiperda*: A Comprehensive Review

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ABSTRACT

Fall armyworm (Spodoptera frugiperda) is one of the most destructive invasive pests affecting maize and other cereal crops worldwide. Since its introduction into Africa in 2016, the pest has spread rapidly across Sub-Saharan Africa and several Asian countries, causing significant yield losses and threatening food security. This review evaluated the occurrence and biocontrol potential of natural enemies of fall armyworm through a systematic assessment of published literature obtained from scientific journals, institutional reports, textbooks, conference proceedings, and online databases. Information on the biology, distribution, natural enemies, and biological control strategies of fall armyworm was synthesized and analyzed.The review revealed that fall armyworm possesses high reproductive capacity, broad host range, and strong dispersal ability, enabling rapid establishment in newly invaded regions. Several natural enemies were identified, including parasitoids, predators, bacteria, viruses, and entomopathogenic fungi. Key parasitoids such as Telenomus remus, Trichogramma pretiosum, Chelonus insularis, and Cotesia marginiventris were found to effectively suppress egg and larval populations. Entomopathogenic fungi including Beauveria bassiana and Metarhizium anisopliae demonstrated considerable pathogenicity, with reported mortality rates ranging from 30% to 87%. Predators such as Doru luteipes, ladybird beetles, ants, and carabid beetles also contributed significantly to reducing pest populations.The effectiveness of natural enemies was influenced by environmental conditions, habitat diversity, cropping systems, and pesticide use. Conservation agriculture, habitat management, and reduced reliance on broad-spectrum insecticides enhanced biological control performance. The review concludes that integrating parasitoids, predators, and microbial pathogens into integrated pest management programs provides a sustainable and environmentally friendly approach for managing fall armyworm populations while reducing dependence on synthetic pesticides and promoting long-term agricultural productivity.

Keywords:
Fall armyworm *(Spodoptera frugiperda);*
Natural Enemies;
Biological Control;
Parasitoids; Predators.

INTRODUCTION

Fall armyworm (FAW), *Spodoptera frugiperda* (Lepidoptera: Noctuidae), is a highly polyphagous pest of maize and other cereals in tropical and subtropical regions of the world (Sparks, 1979). FAW is native to the Americas and its recent invasion in Africa, Asia and Oceania (FAO 2023; Fig. 1) has severely impacted yields of several food crops (Overton *et al.*, 2021). This noctuid pest is highly destructive and the caterpillars can feed on over 350 plant species grown commercially or non-commercially across 76 plant families, with a preference for maize (*Zea mays* L., Poaceae) (Montezano *et al.*, 2018). These caterpillars can feed on different phonological stages of maize and could result in maize yield loss of up to 70% if attacked early growth stage of maize (Hruska, 2019). Owing to the increase in international trade and long-distance migration ability, the FAW has rapidly spread in new geographical regions and threatened global maize production (Early *et al.*, 2018). The high adaptability, fecundity and polyphagous nature made them a key pest of maize in the invaded region under suitable environmental conditions (Jing *et al.*, 2021). Outside its native range, FAW is now recognized as an important pest of maize and several other crops (Rane *et al.*, 2023).

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Within 5 years of invasion in West and Central Africa, and almost 3 years in India, Asia, this pest has changed the pest status of maize and the existing control strategies become less effective (Prasanna *et al.*, 2022). Nevertheless, several control strategies have been deployed against FAW including chemical methods, biological control agents, and physical methods to reduce the crop yield loss (Kenis *et al.*, 2022).

The invasiveness and the destructive nature of FAW have attracted the attention of applied pest management for sustainable crop production (Kumar *et al.*, 2022). In the invaded regions, especially in Africa and Asia, the chemical methods remain a mainstay for FAW control on an emergency basis to reduce crop damage and further spread (Deshmukh *et al.*, 2020). However, several issues remain with chemical control methods due to the heavy application of conventional chemical insecticides such as cypermethrin, lambda-cyhalothrin and chlorpyrifos (Tambo *et al.*, 2019) that cause the development of resistance in FAW populations and redundant use of insecticides kill the nontargets including natural enemies, cause environmental pollution and pose risk to human health (Kebede & Shimalis, 2018).

The long-term use of chemical measures may be ineffective and non-sustainable (Day et al., 2017). Therefore, the development of efficient control measures is the greatest challenge in the invaded region (Guo *et al.*, 2020). However, in the Americas, the use of transgenic *Bt* maize is the leading control approach against FAW, besides the use of insecticides and biological control also used by farmers (Burtet *et al.*, 2017). Consequently, there is a need to develop and introduce safer alternatives, such as biological control against FAW in invaded regions. The rapid spread of *Spodoptera frugiperda* has prompted international collaborations to identify and deploy effective natural enemies. The Food and Agriculture Organization (FAO) has spearheaded initiatives like the Global Action for Fall Armyworm Control, emphasizing biocontrol as a cornerstone for sustainable management (FAO, 2023).

Natural enemies of FAW can now be more easily identified and tracked thanks to developments in molecular tools. DNA barcoding, for instance, has uncovered previously mistaken cryptic parasitoid species in Africa (Kalyebi*et al.*, 2023). According to Zhang *et al.*, (2023), metagenomic techniques have also revealed new entomopathogenic microorganisms linked to FAW cadavers, providing fresh options for the creation of biopesticides. Notwithstanding these advancements, mass raising facilities' lack of infrastructure, farmers' lack of knowledge, and regulatory barriers to microbial pesticide registration make it difficult to scale up biocontrol (Pretty *et al.*, 2024). It is imperative that policymakers prioritize biocontrol research and extension services in order to bridge these gaps. This study intends to evaluate the presence and biocontrol capability of natural enemies in impacted agroecosystems in light of the pressing need for sustainable FAW management.

Origin and Distribution of Fall Armyworm

Although being native to tropical and subtropical regions of Americas, FAW was first detected in Central and Western Africa in early 2016 (Benin, Nigeria, Sao Tome and Principe, and Togo) and further reported and confirmed in the whole of mainland Southern Africa (except Lesotho), in Madagascar and Seychelles (Island State) (FAO, 2018). With the exception of Djibouti, Eritrea, and Lesotho, FAW had been identified and reported in nearly every Sub-Saharan African nation by January 30, 2018 (FAO, 2018). The pest, which is found in 40 sub-Saharan African nations, has already spread to India, where it first appeared in July 2018 (Beshir *et al.*, 2019). FAW population distribution is summarized in Table 1 below:

Table 1: Global distribution of Fall Armyworm

1.	Africa	43
2.	North America	41
3.	Central America	38
4.	South America	28
5.	Asia	9*

Source: (Dively, 2018)

(*= Among the nine countries in Asia, the presence of FAW is unofficial in Thailand)

Fig. 1. Typical morphological marks on medium to large-sized larvae of *S. frugiperda* (a square of 4 pinacula on the 8th terga and an inverted Y shape on the head) and white spots on the tip of the forewing of male moths (CABI, 2017).

Biology of Fall Armyworm

The fall armyworm, *Spodoptera frugiperda* is a moth in the noctuid family indigenous to the Western Hemisphere where it has long been a major agricultural problem for both continents (North and South America) (Nagoshi, Meagher, & Hay-Roe, 2012). It is primarily a pest of maize but has a wide host range and is capable of feeding on over 80 plant species, periodically causing significant economic damage to maize, rice, sorghum, millet, soybean, wheat, alfalfa, cotton, turf, and fodder crops (CABI, 2017; Pogue, 2002) Warm, humid growing seasons with heavy rainfall favour its survival and population buildup, because it cannot develop at temperatures below about 10°c (Stokstad, 2017).

Adults of FAW are nocturnal (CABI, 2017). After a pre-oviposition period of three to four days, the female normally deposits most of her eggs during the first four to five days of life, but some oviposition occurs for up to three weeks (Prasanna *et al.*, 2018). Duration of adult life averages about 10 days, with a range of about 7 to 21 days (Capinera, 2000) and due to the duration of the lifecycle, 2 to 10 generations can be completed in each cropping cycle depending on climate. It is reproductively efficient in tropical areas, where the warmer temperature allows more generations per year compared to temperate areas that may have two or fewer generations in a year. In some tropical and subtropical regions (areas without frost) fall armyworms can produce up to 10 generations during a year (Metcalf, Flint, & Metcalf, 1965).

The number of eggs per female during its lifetime ranged from 1,342 up to 1,844 when larvae were fed millet or corn and soybean leaves, respectively, and 1,839 eggs when fed on cotton (Barros, Torres, & Bueno, 2010). Like all holometabolous, it has four stages to complete its lifecycle namely, egg, larva, pupa and adult (Figure 1). Eggs are usually laid on the upper surface of leaves but occasionally may be deposited on other parts of the host plants. The number of eggs per mass can vary from 100 to 200 (Prasanna *et al.*, 2018). Eggs hatch in two to four days at temperatures ranges of 21–27 °C. The larvae develop through six developmental instars (Fgure:1), with the last instar causing over 70% of the overall damage.

A single larva can consume about 140cm2 of maize leaf area to complete the larval development period. Duration of the larval stage is about 14 days during the summer or 30 days during cool weather (Capinera, 2000). Pupation normally takes place in the soil at a depth 2 to 8 cm (CABI, 2017; Capinera, 2000). The larva constructs a loose cocoon, oval in shape and 20 to 30 mm in length, by tying together particles of soil with silk. If the soil is too hard, larvae may web together leaf debris and other material to form a cocoon on the soil surface.

The pupal stage of FAW cannot enter a diapause period to withstand protracted periods of cold weather or a dry season without host plants (Sparks, 1979). Duration of the pupal stage is about eight to nine days during the summer, but reaches 20 to 30 days during the winter in Florida (Silva *et al.*, 2017). The older larvae of FAW exhibit a cannibalistic behaviour on other smaller larvae, when they co-occur. Cannibalism was found to account for approximately 40% mortality when maize plants were infested with two or four fourth-instar larvae over a three-day period (Chapman *et al.*, 2000). This behaviour, which is different from that of African armyworm (Spodoptera exempta), is accentuated when food is limited and larvae are crowded (Chapman *et al.*, 2000). The role of this density-dependent mortality in the overall population dynamics is unclear (Chapman *et al.*, 1999) but could be an important factor that may reduce the intensity of some outbreaks, although the experience in Africa shows clearly that it does not prevent outbreaks. The high capacity for dispersal of the newly hatched larvae (Pannuti *et al.*, 2016; Rojas, Kolomiets, & Bernal, 2018) should minimize cannibalism when population levels are low.

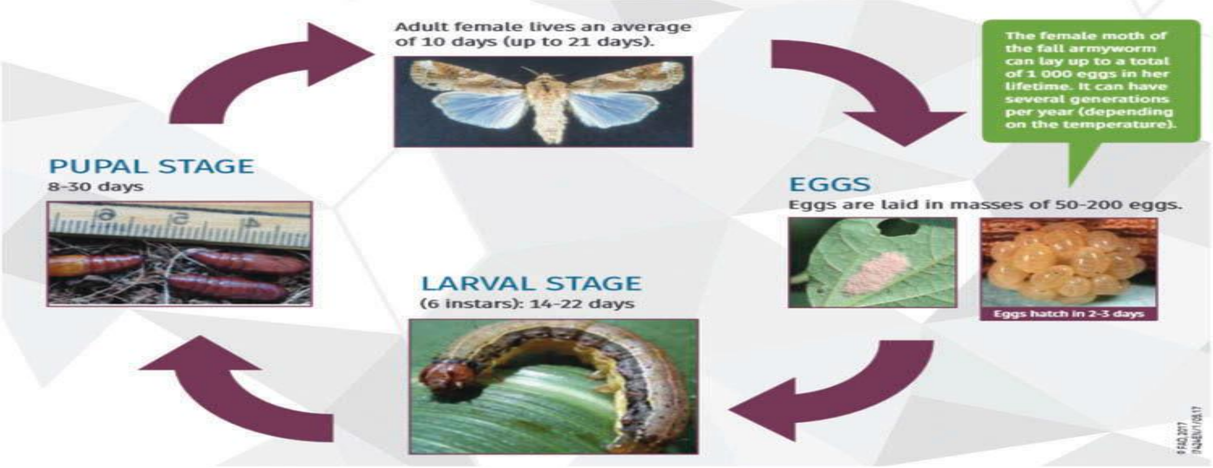

Figure 2: The Lifecycle of Fall Armyworm
Source: Photo by (FAO, 2017)

Table 2: Different Larval Stages of Fall Armyworm

Instars	**Body length (mm)**	**Coloring**	**Marking**
1&2	1.5–3.5	Green with a black head	None
3&4	6–10	Dorsal area tan colour, ventral area green. Lateral white/beige stripes visible	Four dark pinacula or raised spots arranged in a square on the 8th abdominal segment and in a trapezoid on the 9th
5&6	15–40	Light tan, green, black	Four dark pinacula or raised spots arranged in a square on the 8th abdominal segment and a trapezoid on the 9th

Source: (CABI, 2017)

Biological Control

The term biological control of the pest refers to the use of an insect that is the bug's natural enemy to manage a pest in an agricultural field. Predators, parasites, or pathogens can all be used to biologically control pests. One of the key biological agents utilized to manage FAW in vegetable and corn crops is *Telenomus remus*. Because it is so little, it can lay children inside the FAW eggs. These progenies develop and consume the fall armyworm egg. The FAW can be managed because the progeny breaks its shell as it matures into an adult (Agboyi *et al.*, 2020).

Biocontrol Potentials of Natural Enemies of Fall Armyworm

Telenomus or *Trichogramma* wasps are among the best options for potential development of biological control programs targeting FAW eggs (Agboyi *et al.*, 2020). although FAW egg mass scale thickness could lower *Trichogramma* parasitoid performance on this host. (Hou *et al.*,2022). Area-wide releases are made at tactical points (ranging from 20 to 40 per hectare) under 03-day intervals to obtain a constant presence of adult wasps for achieving proactive egg parasitism (Cruz *et al.*, 2016) This improved system is employed early in the season to limit the season-long spread of FAW in egg tracking and destruction (Agboyi *et al.*, 2020). Synchronization in parasitoid release and the existence of FAW egg masses determine the efficacy of applied biocontro. (ICIPE, 2018) However, physically searching for FAW egg masses is a more tiresome activity compared with pheromone traps, regarded as the most effective approach to track the arrival of the FAW moth (FAO, 2018).

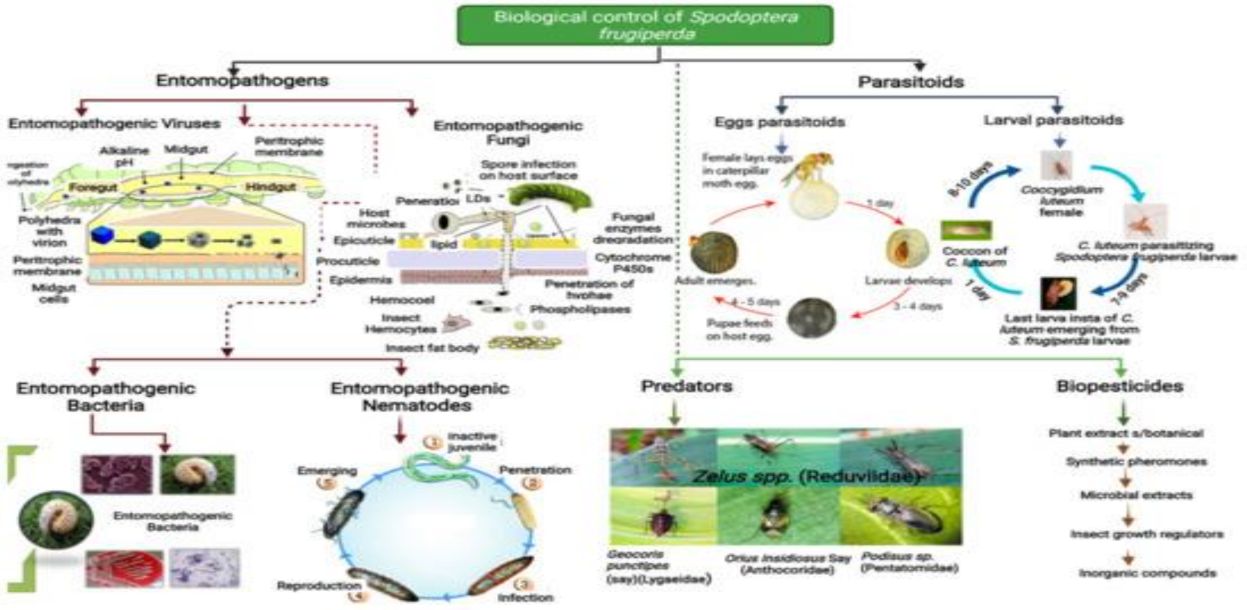

Figure 3. Biological Control of Fall Armyworm (FAW), ***Spodoptera frugiperda***(CABI, 2017).

Categories of Biological Control Agents

i. Parasites

Trichogrammatoidea armigera is used in the control of FAW and helicoverpa eggs which is the main reason of its mass production in the ICRISAT-Niger Laboratory (Prasanna et al., 2018).

Table 3: Parasitic Natural Enemies of Fall Armyworm

S/N	**Natural Enemy**	**Life Stage**	**Host**
1	*Archytas incertus*	Larva	Maize
2.	*Archytas marmoratus*	Larva/Pupae	Maize/Sorghum
3.	*Campoletis flavicincta*	Larva	Maize
4.	*Chelonus curvimaculatus*	Eggs/Larva	Maize
5.	*Chelonus insularis*	Eggs/Larva	Maize/Sorghum
6.	*Cotesia marginiventris*	Larva	Maize
7.	*Cotesia ruficrus*	Larva	Maize
8.	*Euplectrus platyhypenae*	Larva	Maize
9.	*Glyptapanteles creatonoti*	Larva	Maize
10	*Lespesia archippivora*	Larva	Maize
11	*Microchelonus heliopae*	Eggs/Larva	Maize
12	*Brachymeria ovata*	Pupa	
13	*Telenomus remus*	Eggs	Maize/Vegetables
14	*Trichogramma achaeae*	Eggs	Maize
15	*Trichogramma chilotraeae*	Eggs	Maize
16	*Trichogramma pretiosum*	Eggs	Maize
17	*Trichogramma rojasi*	Eggs	Maize

Source: (CABI, 2019)

ii. Pathogens

Entomopathogenic fungi (EPF) can infect several insect species on different stages at a wide range, causing epizootics under certain natural conditions (Alves *et al.*, 2008). Fungal spores of such EPF species infect through integument, and then multiply within the insect's body. After multiplying, EPF releases certain toxins that destroy tissues and the insect dies. The introduction of epizootics depends upon climatic conditions and the frequency of insect contact (Alves *et al.*, 2008). When insects become infected with EPF, they become discolored (cream, green, reddish, or brown), stop eating, and, finally, die as a hard-calcareous cadaver, in which the fungus begins to sporulate (Sujeetha *et al*, 2014). Moisture has an important role for fungi as a biocontrol agent. The most popular fungi for controlling *Spodoptera frugiperda* are *Beauveria bassiana*, *Metarhizium anisopliae*, and *Nomuraea rileyi*, all of which have the potential to be beneficial against insect pests (Sujeetha *et al.*, 2014). FAW larvae are susceptible to *B. bassiana* compared to other lepidopteran pests (Wraight *et al.*, 2010).

In vitro studies showed 30% and 87% mortality when *B. bassiana* and *M. anisopliae* was applied on second instars and eggs, respectively. However, the primary method of identifying a pathogen-infected FAW larva is when it is dead. Dead FAW larvae, especially those infected with baculovirus, are typically found hanging upside down in the higher sections of the maize plant (Prasanna *et al.*, 2018). Table 4 below lists the main entomopathogens that are useful in controlling FAW in maize.

Table 4: Pathogenic Natural Enemy of Fall Armyworm

S/N	**Natural Enemies**	**Life Stages**
1	*Bacillus cereus*	Larva
2	*Bacillus thuringiensis*	Larva
3	*Bacillus thuringiensis alesti*	Larva
4	*Bacillus thuringiensis darmstadiensis*	Larva
5	*Bacillus thuringiensis thuringiensis*	Larva
6	*Bacillus thuringiensis kurstaki*	Larva
7	*Beauveria bassiana*	Eggs/Larva
8	*Granulosis virus*	Larva
9	*Metarhizium anisopliae*	Eggs/Larva
10	*Nucleopolyhedrosis virus*	Larva

Source: (CABI, 2019)

Fig. 4. Different predator insects and entomopathogen recorded from maize farms infested with *S. frugiperda* (a–f) Bugs/Hemiptera (a) Stink bug (*Dalpada trimaculata*), (b) Grass stink bug (Veterna spp.), (c) *Podisus* spp. (d) Seed bug (*Spilostethus pandurus),* (e) Shield bug, & (f) Termite Assassin Bugs; (g) Earwig/Dermaptera (*Doru luteipes*); (h–i) Ladybird beetles/Coleoptera, (h) *Cheilomenes lunata* & (i) *Cheilomenes sulphurea*; (j) Mantidea, and (k) *S. frugiperda* larvae killed by entomopathogen fungus on maize (Photo by: Abera H) (FAO, 2017).

iii. Predators and Parasitoids

There are over 150 known parasitoid species from various parts of the Caribbean and America. Ashley (1979; Ashley et al.). 53 distinct parasitoid species have been reported, including Ophion spp., Chelonus insularis, and Apanteles marginiventris. Tenerucha species. S. frugiperda eggs and larvae include Rogus laphygmae, Campoletis grioti, Ephisoma vitticole, and Meteorus autographae. In America's unsprayed fields, almost 44% of natural parasitism has been identified (FAO, 2017). These species showed at least 45.3% of parasitism level (Sisay *et al.*,2018). Seven species of parasitoids and three species of predators were identified from Ghana to control *S. frugiperda* (Koffi *et al.*, 2020) These seven parasitoid species are listed as *Anatrichus erinaceus* (Loew), *M. testacea*, *C. icipe*, *Bracon* sp., *C. bifoveolatus*, *C. luteum,* and an uncertain *tachinid* fly (Diptera: Tachinidae), while the three species of predators include *Peprius nodulipes* (Signoret), *Haematochares obscuripennis* (Stal), and *Pheidole megacephala* F. (Koffi *et al.*, 2020). The parasitism degree and regional differences in the presence of species have been reported (Koffi *et al.*, 2020). This finding is based on crop stage and type changes, agronomic methods, and geographic regions (Hay-Roe *et al.*, 2016*). Coccygidium luteum* was reported from Kenya and Tanzania, which causes up to 9–19% parasitism in *S. frugipera*. (Sisay *et al.*,2016)

To control the increasing pest population of *S. frugiperda* in America, mass breeding and release of predators and parasitoids have been used to manage other pests (Kumar et al., 2022). In Sub-Saharan Africa, the implementation of classical biocontrol due to its high cost is required by the Government to control *S. frugiperda* (FAO, 2018). Native parasitoids having a better level of parasitism have been observed from different vicinities of SSA (Agboyi 2021). The best way to control FAW is augmentative biocontrol, releasing predators to overcome the increasing pest population of FAW(FAO,2018).

In Africa, Lepidopterous species have been parasitized by C. luteum, the lepidopterous species including *Crypsotidia mesosema* (Hampson), *Spodoptera exigua* (Hübner), *Prophanti ssp*. *Spodoptera exempta* (Walker), *Condica capensis* (Guenée), and *Cydia ptychora* (Meyrick) (Van *et al.*, 2021). Coccygidium luteum has been reported in Africa and many other countries, such as Nigeria, Madagascar, Kenya, Guinea, Congo, Ethiopia, Namibia, Mauritius, Rodrigues Island, Tanzania, Uganda, Somalia, South Africa, and Cameroon (Agboyi *et al*,2020).

Parasitoids can complete several generations in 90 days, leading to the emergence of early-maturing varieties of maize in West Africa (Oluwaranti *et al.*, 2008). Populations of natural enemies are affected due to the occurrence of variation in parasitism (Kogan *et al.*, 1999). These species are; *Trichogramma* spp. *Meteoridea cf, Charops* spp, *Drino quadrizonula* (Thomson), *Metopius discolour* (Tosquinet), *Telenomus remus*, *Chelonus bifoveolatus* (Szpligeti), *Coccygidium luteum*, *Pristomerus pallidus* (Kriechbaumer), and *Cotesia icipe*. (Agboyi *et al.,* 2020) The most preferred site of FAW in maize is the maize whorl inside which a predatory earwig, *Doru luteipes* (Scudder) lays its eggs (Reis *et al.,* 1988) and occurs throughout the maize crop cycle. Nymphs of *D. luteipes* consume 8–12 larvae daily, while in the adult stage they consume 10-21 larvae of *S. frugiperda* daily (Reis *et al.,* 1988). According to (Pasini *et al.,* 2007), the FAW eggs are equal to the insect pupa flour and pollen that are required for the preparation of artificial diets for rearing of *D. luteipes*.

Table 5: Predators of FAW Larva and Pupa in Maize

S/N	Natural Enemy	Life Stage
1	*Calleida decora*	Larva
2	*Calosoma alternans*	Larva
3	*Calosoma sayi*	Larva
4	*Carabidae*	Larva/pupa
5	*Doru luteipes*	
6	*Doru taeniatum*	
7	*Ectatomma ruidum*	
8	*Geocoris punctipes*	

Source:(CABI, 2019)

FACTORS AFFECTING NATURAL ENEMY EFFECTIVENESS

The efficiency of natural enemies in suppressing fall armyworm (Spodoptera frugiperda) populations is influenced by ecological, environmental, and management-related factors. Optimizing biological control techniques across agro-ecological zones requires an understanding of these aspects.

i. **Climate and Environmental Conditions:** Temperature, humidity, and rainfall strongly influence the survival, reproduction, and searching efficiency of parasitoids, predators, and entomopathogens. High temperatures may reduce parasitoid longevity and fecundity, while low humidity can inhibit fungal pathogens such as Metarhizium anisopliae and Beauveria bassiana (Sisay *et al.,* 2019). Viral pathogens such as SfMNPV are also sensitive to ultraviolet radiation, which degrades viral particles on leaf surfaces (Behle & Popham, 2012).

ii. ***Cropping System and Habitat Structure:*** Diversified cropping systems, such as intercropping and agroforestry, enhance natural enemy populations by providing nectar, shelter, and alternative prey. Monoculture maize systems often have reduced natural enemy abundance due to limited ecological niches (Harrison *et al.,* 2019). Habitat complexity increases predator diversity and parasitism rates (Kenis *et al.,* 2019).

iii. ***Pesticide Use and Chemical Interference:*** Broad-spectrum pesticides significantly reduce the abundance and activity of natural enemies. Organophosphates and pyrethroids commonly used against FAW are highly toxic to parasitoids such as Telenomus remus and Cotesia icipe (Agboyi *et al.,* 2020). Sub-lethal pesticide exposure disrupts host-location behaviour and reduces reproductive capacity (Rwomushana *et al.,* 2018).

iv. ***Availability of Alternative Hosts and Prey:*** The presence of alternative hosts supports persistence of parasitoids and predators during periods of low FAW populations. Systems with diverse herbivores maintain higher levels of natural enemies, while landscapes with limited prey may experience reduced effectiveness (Abrahams *et al.,* 2017).

v. ***Landscape Composition and Surrounding Vegetation:*** Natural enemies depend on semi-natural habitats that provide refuge and resources. Intensive agricultural landscapes show reduced parasitoid and predator richness (Hay-Roe *et al.,* 2016). Connectivity between natural habitats and croplands enhances natural enemy spillover into maize fields (Kenis *et al.,* 2019).

vi. ***Biological Characteristics of Natural Enemies:*** Differences in host specificity, searching efficiency, and adaptability influence natural enemy performance. For example, Telenomus remus shows high host specificity and efficient egg-mass detection, giving it strong biocontrol potential. Generalist predators such as ants and spiders vary in effectiveness depending on prey dynamics (Sisay *et al.,* 2019).

vii. ***Human Agricultural Practices:*** Cultural practices such as tillage, sanitation, crop residue burning, and mulching influence natural enemy survival. Conservation agriculture practices promote predators and entomopathogens, while farmer awareness affects protection of natural enemies (Harrison *et al.,* 2019)

MANAGEMENT OF THE FALL ARMYWORM

The sustainable management of the Fall Armyworm (*Spodoptera frugiperda*) has transitioned from emergency chemical responses to long-term ecological strategies. Current research emphasizes the conservation and augmentation of natural enemies as the primary pillar for maintaining pest populations below economic thresholds without degrading the environment (Ghafar & Ramzan, 2024).

Based on recent comprehensive reviews of occurrences and bio-control potential, the following recommendations are central to sustainable management:

1. Conservation of Indigenous Natural Enemies

Indigenous natural enemies already present in local ecosystems provide "cost-free" biological control. Managing the farm environment to protect these organisms is critical.

Identify and Protect Key Taxa: Farmers should be trained to recognize common predators such as Coleopterans (Coccinellidae family) and earwigs, as well as parasitoids from the Braconidae (Hymenoptera) and Tachinidae (Diptera) families (Gallegos Morales et al., 2025).

2.Avoid Non-Selective Pesticides: Indiscriminate use of broad-spectrum synthetic pesticides must be avoided, as they disrupt ecological resilience and kill the "farmer's best friends" (FAO, 2026).

Enhance On-Farm Biodiversity: Practice intercropping with legumes (beans, pigeon pea) or ornamental flowering plants to provide alternative food sources and habitats for natural enemies (Ghafar & Ramzan, 2024; Acta Scientific, 2025).

3. Utilization of Microbial Biocontrol Agents (Entomopathogens)

Microbial agents offer a targeted approach that affects specific life stages of the pest while remaining safe for non-target organisms.

4.Deploy Fungal and Viral Pathogens: The use of entomopathogenic fungi such as *Metarhizium anisopliae* and *Beauveria bassiana*, along with Baculoviridae viruses, effectively disrupts FAW development (Gallegos Morales et al., 2025).

5.Integrate Plant-Microbial Synergies: Combined applications of plant bio-extracts (e.g., neem and moringa) with maize-associated bacterial isolates have shown larval mortality rates up to 80% (PMC, 2026).

Focus on Early Life Stages: Biocontrol interventions are most effective against early larval stages; therefore, early-season monitoring is vital (Acta Scientific, 2025; PMC, 2026).

6. Cultural and Agronomic Synchronization

Sustainable management requires aligning crop cycles with pest-free windows and improving plant vigor.

7.Adopt Early Sowing Windows: Timely planting (immediately after the first three major rains) allows the crop to pass through its most vulnerable stages before FAW populations peak (FAO, 2026).

8.Practice Good Soil Management: Healthy plants recover more easily from defoliation. Using natural fertilizers like manure or compost enhances soil biological activity, which indirectly supports a robust habitat for natural enemies (FAO, 2026).

9.Implement "Push-Pull" Technology: Using repellent plants (push) within the field and trap crops (pull) at the borders naturally reduces infestation levels (Acta Scientific, 2025).

10. Precision and Innovative Interventions

New technologies are being integrated into biological control frameworks to increase efficiency.

11.Leverage AI and Drone Technology: The integration of AI-driven systems and drones for the precision release of biocontrol agents (like *Trichogramma spp.*) allows for large-scale management without chemical drift (Ghafar & Ramzan, 2024).

12.Use Mechanical Physical Controls: For smallholders, regular field visits to hand-pick egg masses or apply dry sand/ash into the whorls of infested plants remain effective, low-cost options (Acta Scientific, 2025).

MATERIALS AND METHODS

This study adopted a systematic review approach to evaluate the occurrences and biocontrol potential of natural enemies of fall armyworm, Spodoptera frugiperda, in different agroecosystems. Information used in this review was obtained from published scientific journals, conference papers, textbooks, institutional reports, and online databases related to fall armyworm biology, distribution, and biological control strategies. Relevant literature was sourced from databases such as Google Scholar, Research Gate, FAO, and CABI.

The review focused on publications discussing the origin, biology, distribution, occurrence, and management of fall armyworm, particularly studies involving parasitoids, predators, and entomopathogenic microorganisms used as biological control agents. Literature published between 1979 and 2026 was critically examined to obtain comprehensive information on the pest and its natural enemies. Relevant keywords used during literature search included “fall armyworm”, “*Spodoptera frugiperda*”, “biological control”, “parasitoids of fall armyworm”, “predators of fall armyworm”, “entomopathogenic fungi”, and “natural enemies of maize pests”. Studies were selected based on their relevance to the objectives of the review and the reliability of the source.

Data extracted from the reviewed materials included:

- Distribution and occurrence of fall armyworm in different regions.
- Biological characteristics and lifecycle of the pest.
- Types of natural enemies associated with fall armyworm.
- Biocontrol effectiveness of parasitoids, predators, and pathogens.
- Factors influencing the efficiency of natural enemies.
- Sustainable management strategies involving biological control agents.

The data gathered from the chosen research was meticulously arranged into thematic sections and tables. The efficacy of various natural enemies against fall armyworm infestation in maize and other cereal crops was compiled by comparative study. A thorough grasp of the function of biological control in sustainable fall armyworm management was produced by synthesizing and descriptively interpreting the results from multiple authors.

RESULTS AND DISCUSSION

According to the assessment, one of the most damaging invasive pests affecting maize and other cereal crops worldwide is Spodoptera frugiperda. Originally from the Americas, the pest quickly expanded throughout Africa and Asia after being discovered in West and Central Africa in 2016. According to reports, the insect is currently found in various Asian nations as well as more than 40 countries in Sub-Saharan Africa.The findings indicated that fall armyworm possesses high reproductive and dispersal capacity, enabling rapid population establishment in invaded regions. Adult females were reported to lay between 1,342 and 1,844 eggs during their lifetime, while larvae pass through six developmental instars, with the final larval stages causing the greatest damage to maize plants. Yield losses of up to 70% were reported in severely infested maize farms. Several categories of natural enemies associated with fall armyworm control were identified. These included parasitoids, predators, bacteria, viruses, and entomopathogenic fungi. Among the parasitoids, species such as *Telenomus remus*, *Trichogramma pretiosum*, *Chelonus insularis*, and *Cotesia marginiventris* were frequently reported as effective biological control agents. These parasitoids significantly reduced egg hatchability and larval survival in maize fields.

The review further showed that entomopathogenic fungi such as and *Metarhizium anisopliae* demonstrated strong pathogenic activity against fall armyworm larvae and eggs. Laboratory studies reported mortality rates ranging from 30% to 87% depending on fungal species and insect developmental stage. Viral pathogens such as nucleopolyhedro viruses also contributed significantly to larval mortality.

Predatory *Beauveria bassiana* insects including *Doru luteipes*, ladybird beetles, ants, and carabid beetles were also identified as important biological control agents. Adult and nymph stages of *Doru luteipes* consumed several fall armyworm larvae daily, thereby reducing pest population density in maize farms.

The study also showed that farming practices, pesticide use, habitat variety, and environmental variables all have a significant impact on how effective natural enemies are. While conservation agriculture and diverse cropping systems increased the abundance of natural enemies and the effectiveness of biological control, high pesticide use decreased parasitoid and predator populations. All things considered, the results showed that biological management is still a viable and environmentally sound method of controlling fall armyworm populations. Sustainable maize production can be enhanced and reliance on synthetic insecticides can be greatly decreased by incorporating parasitoids, predators, and microbial diseases into integrated pest management strategies.

The findings of this review demonstrate that Spodoptera frugiperda remains one of the most destructive invasive pests threatening global maize production, particularly in Africa and Asia. Its rapid spread across several continents within a short period confirms the strong migratory ability and adaptive capacity of the pest. Similar observations were reported by Early et al. (2018) and FAO (2018), who noted that international trade, favorable climatic conditions, and long-distance migration contributed significantly to the rapid establishment of FAW populations in newly invaded regions.

The high reproductive potential and polyphagous feeding behavior of FAW greatly contribute to its economic importance. The ability of female moths to lay over 1,800 eggs during their lifespan, coupled with the occurrence of multiple generations annually in tropical environments, explains the persistent outbreaks observed in maize-growing regions. This agrees with the findings of Barros et al. (2010) and Metcalf et al. (1965), who reported that warm environmental conditions favor rapid population build-up of the pest. Furthermore, the severe feeding damage caused by the later larval instars supports the report of Hruska (2019), who observed yield losses of up to 70% in heavily infested maize fields.

The review further revealed that biological control offers a sustainable and environmentally friendly alternative to excessive reliance on synthetic insecticides. Egg parasitoids such as Telenomus remus and Trichogramma pretiosum were identified as highly effective natural enemies because they attack FAW during its early developmental stages, thereby preventing larval emergence and subsequent crop destruction. Cruz et al. (2016) and Hou et al. (2022) similarly reported that augmentative release of egg parasitoids significantly reduced FAW populations in maize fields. However, the effectiveness of these parasitoids may be influenced by egg mass characteristics and synchronization between parasitoid release and pest occurrence.

Larval parasitoids such as Chelonus insularis and Cotesia marginiventris were also reported to contribute substantially to natural suppression of FAW populations. Studies from Ghana, Kenya, and Tanzania demonstrated varying parasitism levels depending on environmental conditions, cropping systems, and geographical location. This indicates that successful biological control depends largely on ecological compatibility between the natural enemy and the pest population. Similar conclusions were drawn by Sisay et al. (2016) and Koffi et al. (2020), who observed regional differences in parasitoid abundance and effectiveness.

Entomopathogenic fungi including Beauveria bassiana and Metarhizium anisopliae demonstrated considerable pathogenic activity against FAW eggs and larvae. Mortality rates ranging from 30% to 87% indicate the strong potential of microbial agents in integrated pest management programs. These findings support previous reports by Wraight et al. (2010) and Sujeetha et al. (2014), who emphasized the importance of fungal pathogens in controlling lepidopteran pests. The ability of these fungi to infect insects through the integument and multiply within the insect body makes them highly valuable biological control agents. Nevertheless, environmental factors such as humidity and temperature strongly influence fungal performance, which may limit their effectiveness under unfavorable field conditions.

Predatory insects were also identified as important contributors to FAW suppression. Species such as Doru luteipes, ladybird beetles, ants, and carabid beetles consume large numbers of FAW larvae daily, thereby reducing pest population density. The high predatory capacity of Doru luteipes observed in this review corroborates the findings of Reis et al. (1988), who reported that both nymphs and adults actively prey on FAW larvae throughout the maize cropping cycle. Predators therefore complement parasitoids and pathogens in maintaining ecological balance within agroecosystems. The review also established that environmental and management factors greatly influence the effectiveness of natural enemies. Excessive application of broad-spectrum insecticides was found to reduce populations of beneficial organisms and interfere with their reproductive and searching behaviors. Similar observations were made by Rwomushana et al. (2018), who reported that pesticide misuse negatively affects parasitoids and predators. Conversely, diversified cropping systems, agroforestry, and conservation agriculture practices enhance habitat complexity and provide shelter, nectar, and alternative hosts for natural enemies. Harrison et al. (2019) and Kenis et al. (2019) similarly emphasized that ecological intensification improves biological control efficiency in maize production systems.

Recent advances in molecular biology and precision agriculture have further improved biological control prospects against FAW. DNA barcoding and metagenomic studies have facilitated accurate identification of parasitoids and discovery of new entomopathogens associated with FAW populations. Additionally, technologies such as drone-assisted release of parasitoids and AI-based pest monitoring may enhance large-scale implementation of biological control programs. However, limitations including poor farmer awareness, inadequate infrastructure for mass rearing, and regulatory constraints affecting microbial pesticide registration continue to hinder widespread adoption of these sustainable technologies.

Overall, the findings of this review highlight the importance of integrating parasitoids, predators, and entomopathogenic microorganisms into comprehensive integrated pest management strategies for sustainable suppression of FAW populations. Biological control not only reduces dependence on synthetic insecticides but also promotes environmental conservation, biodiversity protection, and long-term agricultural sustainability.

CONCLUSION

The rapid global spread and destructive capacity of *Spodoptera frugiperda* present significant challenges to maize-based food systems, particularly in Africa and Asia where its invasion has been most severe. Biological control offers a long-term, environmentally safe, and economically viable alternative to chemical pesticide reliance. The diversity of natural enemies including parasitoids, predators, and entomopathogenic microbes provides multiple avenues for integrated pest management. Egg parasitoids such as *Telenomus remus* and *Trichogramma* spp. remain the most effective biocontrol agents, while larval parasitoids like *Chelonus insularis* and fungal pathogens such as *B. bassiana* contribute substantially to reducing larval populations. However, the efficiency of these natural enemies is highly dependent on climatic conditions, cropping system design, pesticide use, and landscape structure. Enhancing habitat complexity, reducing harmful pesticide applications, and promoting conservation agriculture can significantly improve natural enemy performance.

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