



Review

Biological Control of Fall Armyworm, *Spodoptera frugiperda*

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Abstract: The fall armyworm (FAW), *Spodoptera frugiperda*, is one of the most important invasive pests worldwide, resulting in considerable losses in host crops. FAW comprises two genetic strains, such as the “rice strain”, which prefers rice and other grass species, and the “maize strain”, which feeds upon maize and sorghum. Potential control measures are generally more applicable to the farmers who lack financial assets to buy chemical insecticides or costly pure seeds. The adverse effects of pesticides on the ecosystem and human’s health and the development of resistance to insect pests have exaggerated efforts to find an alternative strategy that is cost-effective, low-risk and target-specific. Therefore, biological control is widely considered as one of the most important options for insect pest management. This comprehensive review amasses the information on biological control in all phases of their development, including predators, parasitoids, entomopathogenic fungi, viruses, nematodes, bacteria, and biopesticides, with a special focus on their effectiveness against FAW. The findings regarding biological control are briefly discussed in light of improving management programs of the invasive pest *S. frugiperda*.

Keywords: FAW; biopesticides; predators; parasitoids; entomopathogenic microorganisms; integrated pest management



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1. Introduction

The fall armyworm (FAW), *Spodoptera frugiperda*, is the most important pest worldwide, resulting in considerable yield losses in maize. FAW was first reported in 1797 as a devouring pest endemic to subtropical and tropical regions of America. It belongs to the family Noctuidae under the order Lepidoptera and was first reported in the African continent [1]. FAW is a devastating pest that damages 186 plant species belonging to 42 families. Poaceae, Fabaceae, Solanaceae, Asteraceae, Rosaceae, Chenopodiaceae, Brassicaceae, and Cyperaceae are mostly affected. It results in about 58% yield loss in maize [2,3]. FAW is known to feed voraciously on more than 350 plant species, especially maize, rice, and sorghum, which might cause significant agricultural losses worldwide [3–5]. The first confirmed reports of FAW invasion were documented from West Africa in early 2016, and then spread throughout sub-Saharan Africa and Southeast Asia [1,6]. Now, this pest has been spread in more than 109 countries [3]. In India, it was first identified in May 2018, causing major losses to farmers in Karnataka and other southern Indian states [7]. FAW was first discovered in Nepal in May 2019 through morphological and genetic identification approaches [8].

FAW is an important notorious pest which attacks maize and various other crops belonging to the family Gramineae [9]. It is a polyphagous insect pest with over 80 host plants that causes severe damage to cereal crops and vegetables [1,10,11]. The young curl of leaves, ears, and tassels have been preferred, resulting in significant loss to maize crop [12]. FAW travels approximately 500 km before starting oviposition [10]. A single generation of FAW moths can disperse more than 500 km distance from the emergence location, owing to the wind, until they are sexually mature [11,13,14].

FAW is comprised of two genetic strains: the “rice strain”, which prefers rice and other grass species, and the “maize strain”, which feeds primarily on maize and occasionally on sorghum [15]. When FAW arrives in large numbers, especially with an offensive effect, it is determined to pose a long-term and damaging threat to many important crops, as the surrounding circumstances provide a comfortable environment for a variety of host plant species pre-favorable weather conditions for reproduction in various areas [1,4,16].

Biological control strategies are more appropriate to farmers who do not have the financial capability to purchase chemical insecticides and expensive seeds [17]. Microbial formulations are available in the market that are made from pathogens, arthropod natural enemies, and are more profitable in agricultural systems [3,18]. Recently, the microbial formulation production costs have been significantly reduced because these are mainly mass produced in liquid medium [3,19]. The repetitive use of synthetic pesticides in the field may prove detrimental to humans and the environment, have increased input cost, and, furthermore, initiate resistance and resurgence [20–25]. The larvae of the FAW caterpillar are deeply embedded in the leaf curls and corn ears, resulting in control failures. However, it comes to feed on plants at night or dawn and twilight [26].

What are the Biological and Biorational Pest Control Options?

The easiest way to manage the insect pest outbreak is to formulate a self-propelling and self-perpetuating system for the restoration or stimulation of self-sustainable biological control tactics. Biological control agents, such as predators, parasitoids, and pathogens, were supplied to keep close synchronization of the community of other organisms. *Trichogramma* and *Telenomus* are the most active biological control agents, which parasitized the FAW eggs and other key pests [27,28]. Parasitoids are closely associated with one of the pest stages and have a higher level of specificity [29]. Predators are rarely linked with a specific insect pest. They feed on the prey with a lower trophic level of specificity than other animals, e.g., the earwigs, ladybird beetles, podisus, and orius prey on different life stages of FAW. Entomopathogens include bacteria, fungi, viruses, protozoans, and nematodes that are the main cause of disease in insects. FAW was infected by several entomopathogens, including *Bacillus thuringiensis* (Bt), *Metarhizium anisopliae*, *Beauveria bassiana*, and *Spodoptera frugiperda* multiple nucleopolyhedroviruses (SfMNPV) (Figure 1).

In agricultural systems, certain arthropods and microbial pathogens have been used as biocontrol agents [18,30]. Biological pest management is a powerful tool for plant protection [30]. Four hymenopteran and one dipteran species from Kenya, Tanzania, and Ethiopia have been identified, including *Chelonus curvimaculatus* Cameron (Braconidae), *Charops ater* Szepliget (Ichneumonidae), *Coccygidium luteum* (Brulle) (Braconidae), and one parasitoid of Diptera *Palexorista zonata* (Curran) (Tachinidae) [31]. The level of parasitism varies in different parasitoids. *Cotesia icipe* was the dominant larval parasitoid, showing a level of parasitism in Ethiopia ranging from 33.8% to 45.3% [31]. In Kenya and Tanzania, *P. zonata* parasitizes 12.5%, whereas *C. luteum* parasitizes 04 to 8.3% [31]. The parasitism levels of two parasitoids, *C. luteum* and *Charops ater*, in Kenya and Tanzania, were 04–8.3% and 06–12%, respectively [32]. The most encouraging point under this prospect is the presence of natural enemies despite express invasion and speedy damaging habit of FAW.

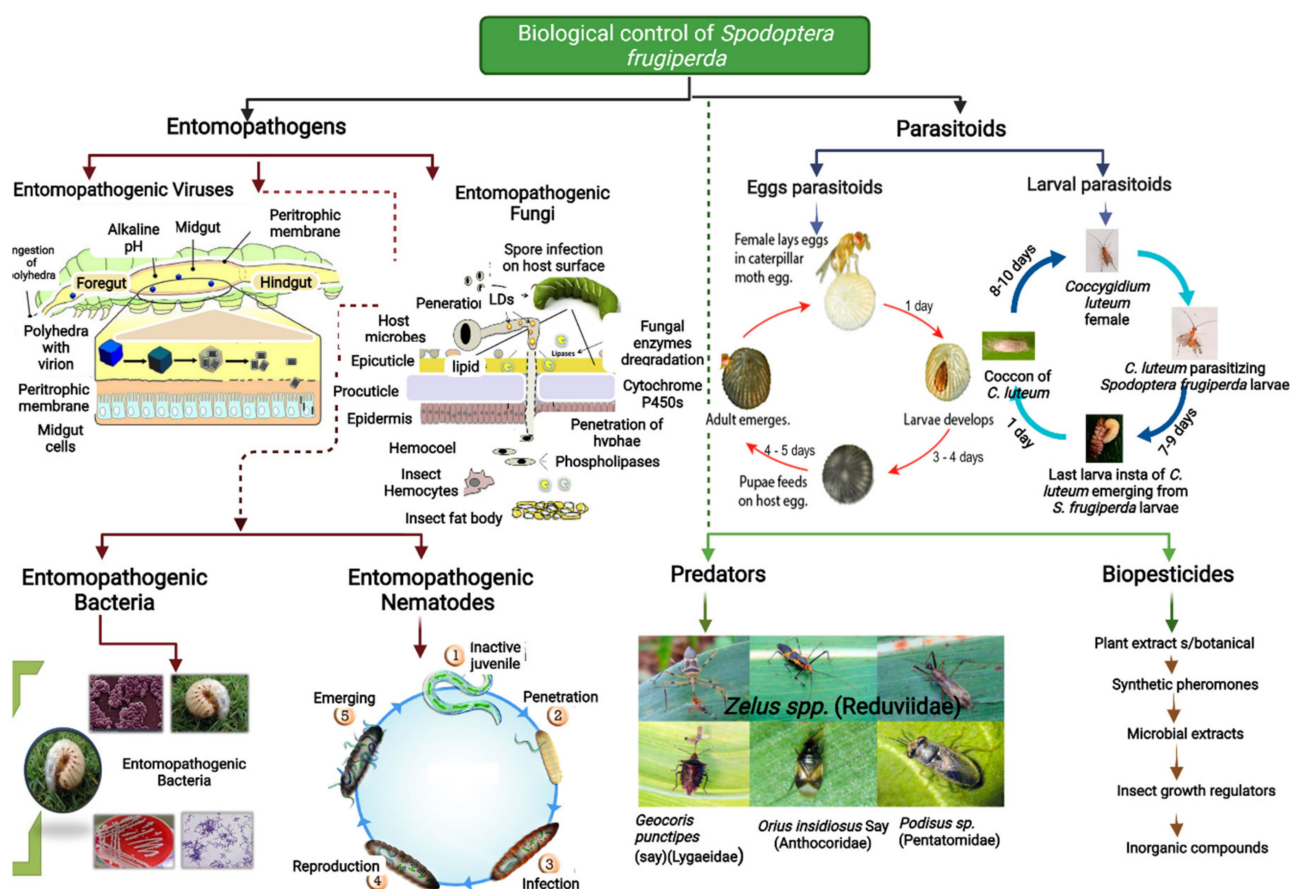


Figure 1. Biological control of fall armyworm (FAW), *Spodoptera frugiperda*.

Biological Control agent: a contemporary release against FAW

Telenomus or *Trichogramma* wasps are among the best options for potential development of biological control programs targeting FAW eggs [33], although FAW egg mass scale thickness could lower *Trichogramma* parasitoid performance on this host [34]. 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 [35]. This improved system is employed early in the season to limit the season-long spread of FAW in egg tracking and destruction [33]. Synchronization in parasitoid release and the existence of FAW egg masses determine the efficacy of applied biocontrol [36]. 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 [37–39].

In the Natural Control of FAW, the importance of another beneficial insect

Maize fields (in the Caribbean and America) include a diverse range of beneficial insects [40]. *Chelonus insularis* is one of the major biological control agents that parasitize the eggs of FAW under natural conditions [41]. However, FAW eggs hatch into the larvae and release the parasitized adult from the larva of FAW [41]. *Trichogramma* and *Telenomus* wasps are smaller and less competitive than *Chelonus* wasps; thus, they have a better chance of surviving [41]. The parasite larvae's food consumption is steadily reduced, with less than 10% of the biomass eaten by the borehole larvae [42]. The presence of young larvae in the FAW release zone does not necessarily mean that there has been a failure in the biological control of FAW [42]. Deployment of a conservation technique will sustain the natural biological control agents for obtaining a self-perpetuating and self-propelling organized agro-ecosystem. More information is given on the role of *Chelonus* in IPM [43,44].

In addition to *C. insularis*, many other parasitoid species are also observed in suppressing populations of FAW larvae [45]. *Campoletis flavicincta* has been extensively used to suppress the FAW population [46]. Insect predators consume both larvae and eggs that necessarily maintain the FAW population to a sub-economic level [47]. For example, during the maize crop cycle, the predatory earwig *Doru luteipes* (Scudder) lays its eggs within the maize whorl [47]. *Doru luteipes* nymphs consume 8–12 larvae per day, while adults consume 10–21 *S. frugiperda* larvae daily [47]. The comprehensive demonstration of biocontrol is shown in Figure 1. Microorganisms, such as *Baculovirus* or *Bacillus thuringiensis*, should be considered in situations where the presence of biocontrol agents is not yet optimal and pesticide applications are needed [45,48].

2. Categories of Biological Control Agents

Predators and Parasitoids

About 150 parasitoid species have been identified from different regions of America and Caribbean. Ashley [49] reported 53 different parasitoid species, including *Apanteles marginiventris*, *Chelonus insularis*, *Ophion* spp. *Ternelucha* spp. *Rogus laphygmae*, *Campoletis grioti*, *Ephiosoma vitticole*, and *Meteorus autographae* in *S. frugiperda* eggs and larvae. More than 44% of natural parasitism has been recorded in the non-sprayed fields of America [13]. These species showed at least 45.3% of parasitism level [50]. Seven species of parasitoids and three species of predators were identified from Ghana to control *S. frugiperda* [51]. 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), *Haematochara obscuripennis* (Stal), and *Pheidole megacephala* F. [51]. The parasitism degree and regional differences in the presence of species have been reported [50–52]. This finding is based on crop stage and type changes, agronomic methods, and geographic regions [53,54]. *Coccygidium luteum* was reported from Kenya and Tanzania, which causes up to 9–19% parasitism in *S. frugiperda* [50].

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 [2,37–39] (Tables 1 and 2). In Sub-Saharan Africa, the implementation of classical biocontrol due to its high cost is required by the Government to control *S. frugiperda* [37]. Native parasitoids having a better level of parasitism have been observed from different vicinities of SSA [33,50–52]. The best way to control FAW is augmentative biocontrol, releasing predators to overcome the increasing pest population of FAW [37] (Table 1). In America, *Trichogramma* parasitoids have been used to efficiently control the eggs of *S. frugiperda* [10,39] (Table 2). Scientists at ICIPE in Kenya and Agboyi et al. [33] observed that *Trichogramma* and *Telenomus* parasitoid can efficiently augmentative biocontrol against *S. frugiperda*. Before FAW neonates emerge, parasitoids (*Trichogramma* and *Telenomus*) are introduced into maize fields, search for FAW egg masses, and lay their eggs on them to limit the FAW population at the egg stage [36].

In Africa, Lepidopterous species have been parasitized by *C. luteum*, the lepidopterous species including *Crypsotidia mesosema* (Hampson), *Spodoptera exigua* (Hübner), *Prophantia* ssp. *Spodoptera exempta* (Walker), *Condica capensis* (Guenée), and *Cydia ptychora* (Meyrick) [55]. *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 [33]. *Coccygidium luteum* is a solitary koinobiont parasitoid that belongs to the Braconid subfamily Agathidinae, which includes more than 46 species [56,57]. As biocontrol agents, Agathidinae species in this subfamily are not well known regarding their efficacy against insect pests and are rarely studied [58]. In China, *C. luteum* controls the eggs of many *Spodoptera* species [59,60]. The comprehensive demonstration of biocontrol is shown in Figure 1. Parasitoids can complete several generations in 90 days, leading to the emergence of early-maturing varieties of maize in West Africa [61]. Populations of natural enemies are affected due to the occurrence of variation in parasitism [62]. In the United States, parasitism levels were lower on average

than previously reported levels, i.e., 15.5% [63], 35% [64], 8.1% [65], 28.3% [41], 18.3% [66], and 13.8% [67]. Agboyi et al. [33] reported parasitoids of 10 different species from the various localities of Ghana and Benin. These species are *Trichogramma* spp. *Meteoridea* cf. *Charops* spp, *Drino quadrizonula* (Thomson), *Metopius discolour* (Tosquinet), *Telenomus remus*, *Chelonus bifoventolatus* (Szpligeti), *Coccygidium luteum*, *Pristomerus pallidus* (Kriechbaumer), and *Cotesia icipe* [33]. Introduction, conservation, and augmentation are the three basic techniques for promotion of a biological control system in an ecosystem. Hymenoptera insects act as egg and larval parasitoids that are collected from FAW-infested areas. Further assistance might be given to stabilize the system either through inoculative or inundative releases. This manipulation chiefly increased the effectiveness of natural enemies.

Table 1. Predators against *Spodoptera frugiperda*.

Scientific Name	Family	Order	Description	Reference
Earwigs: (a) <i>Doru luteipes</i> (Scudder)	Forficulidae	Dermaptera	Very important parasitoid of FAW. According to bioecological studies feeding on FAW larvae, the number of eggs per oviposition is 25–30, with an incubation period of about one week	[68]
(b) <i>Euborellia annulipes</i> (Lucas)	Anisolabididae	Dermaptera	A very important parasitoid of <i>Spodoptera frugiperda</i> also feeding on FAW larvae	[69]
Flower bug <i>Orius insidiosus</i> (Say)	Anthoridae	Heteroptera	Extremely abundant species are mostly used in biological control programs. They prey on small arthropods, such as aphids, thrips, whiteflies, mites, and lepidopteran eggs	[70]
Ground beetle <i>Calosoma calidum</i> (Fabricius)	Carabidae	Coleoptera	After mating, the females lay their eggs on the soil's surface or just below it. Before pupation in the ground, the immature stage goes through 3 instars	[71]
Spined soldier bug <i>Podisus maculiventris</i> (Say)	Pentatomidae	Heteroptera	Lepidopteran larvae are the primary food source for nymphs and adults. It pierces its prey and injects a toxin that causes it to become paralyzed in a short period. The predator sucks out the prey's internal fluids, killing it	[72]
Assassin bug <i>Pristhesancus plagipennis</i> (Walker)	Reduviidae	Hemiptera	The genus <i>Zelus</i> is the most common killer bug in maize. Females lay their eggs in clusters on plant leaves or even on the ground. The nymphs are wingless and look like adults	[73]
Pirate bug <i>Orius sauteri</i> (Poppius)	Anthoridae	Hemiptera	An important parasitoid. Moth eggs, aphids, and small Lepidoptera larvae are all prey for <i>O. sauteri</i>	[74]

Table 2. Parasitoids against *Spodoptera frugiperda*.

Scientific Name	Family	Order	Description	Reference
<i>Trichogramma pretiosum</i> (Riley)	Trichogrammatidae	Hymenoptera	Egg parasitoids, used in the control of eggs of FAW and <i>Helicoverpa</i> spp.	[75]
<i>Trichogrammatoidea armigera</i> (Nagaraja)	Trichogrammatidae	Hymenoptera	Egg parasitoids, used in the control of eggs of <i>Helicoverpa armigera</i> and FAW	[76]
<i>Telenomus remus</i> (Nixon)	Scelionidae	Hymenoptera	Egg parasitoid, shows more than 45% parasitism level [31]. <i>Telenomus remus</i> completes its life cycle within 12–13 days at 25 °C, and its female parasitizes more than 250 eggs in [77]	[75]
<i>Chelonus insularis</i> (Cresson)	Braconidae	Hymenoptera	Egg–larval parasitoids, The female <i>Chelonus</i> lays eggs inside the eggs of fall armyworm, and the larva, which is parasitized, steadily curtails down its feeding until its death happens	[78]
<i>Chelonus bifoveolatus</i> (Szpligeti)	Braconidae	Hymenoptera	Egg–larval koinobiont endoparasitoid, mostly attack the insects belonging to the family of Pyralidae and Noctuidae. The parasitoid attacks by ovipositing into the host eggs [66]	[51]
<i>Campoletis sonorensis</i> (Cameron)	Ichneumonidae	Hymenoptera	Larval parasitoids, females lay eggs within the first, second, and third instars of the FAW, and the larva completes its life cycle by feeding on the pest's internal contents. For the parasitoid, the third-instar larvae are the most favorable stage	[78]
<i>Charops</i> sp.	Ichneumonidae	Hymenoptera	Larval parasitoids, used to control FAW population on the larval stage.	[33]
<i>Cotesia icipe</i> (Fernández-Triana & Fiaboe)	Braconidae	Hymenoptera	Larval parasitoids, also Lepidopterous larvae and eggs of FAW have been parasitized by <i>C. icipe</i> [79], and the larval instars of 1st and 2nd stage have been parasitized too [80].	[81]
<i>Habrobracon hebetor</i> (Say)	Braconidae	Hymenoptera	Larval parasitoids, under laboratory conditions, a small wasp that has been used to combat the pearl millet head miner, often targets FAW larvae.	[33]
<i>Coccygidium luteum</i> (Brullé)	Braconidae	Hymenoptera	Larval parasitoids internally attack larvae belonging to the Noctuidae family [82]. An idiobiont ectoparasitoid <i>Bracon</i> sp. of <i>C. luteum</i> hiddenly attacks the larvae of cereal stored products and cereal stem borers and is also used against <i>S. frugiperda</i> [31,50,83,84].	[33]
<i>Winthemia trinitatis</i> (Thompson)	Tachinidae	Diptera	Larval parasitoids, the female lays her eggs near the head of a fifth- or sixth-instar FAW, making it difficult to detach. The parasitoid's larvae enter the larva's body, delaying the pupation and resulting in up to 30% parasitism.	[85]

Table 2. Cont.

Scientific Name	Family	Order	Description	Reference
<i>Drino quadrizonula</i> (Thomson)	Tachinidae	Diptera	Larval parasitoids, parasitized family of Noctuidae and other <i>Spodoptera</i> spp.	[86]
<i>Archytas marmoratus</i> (Townsend)	Tachinidae	Diptera	Larval–pupal parasitoids, several species of Noctuidae (Lepidoptera), including FAW. Eggs are not laid directly on the host but instead scattered them around. Hatching takes place, and the young larvae emerge. When these larvae come into contact with a host and invade the host’s body, parasitism occurs.	[50]
<i>Lespesia archippivora</i> (Riley)	Tachinidae	Diptera	Larval–pupal parasitoids, on the back end of the caterpillar, the female oviposits. <i>Lespesia archippivora</i> has three instars that feed on the host caterpillar, and when they reach maturity, the parasitoid emerges from the larva and pupates in the soil.	[87]

3. Microorganisms

Entomopathogens infect and cause diseases in insects, and include viruses (*Spodoptera frugiperda* multiple nucleopolyhedrovirus), bacteria (*Bacillus thuringiensis*), fungi (*Metarhizium anisopliae* and *Beauveria bassiana*), nematodes, protozoans, and others that are well known against FAW management.

3.1. Entomopathogenic Viruses

Virus-based insecticides among microbial control agents within the *Baculovirus* group have been recognized with higher potential as bioinsecticides for growth and development because of their specific characteristic nature, higher virulence against the host, and increased safety towards vertebrates [88,89]. Two variants of *Baculovirus* have been studied to control *S. frugiperda*, named granulovirus “SfGV”, which is *Betabaculovirus*, and multiple nucleopolyhedroviruses “SfMNPV”, which is *Alphabaculovirus*. However, the SfMNPV has a good ability to manage FAW [90–92]. SfMNPV is specific to FAW larvae. The pest becomes infected by ingesting contaminated (maize leaf) food in natural conditions [93]. After ingestion, polyhedral inclusion bodies (PIB) dissolve in an alkaline midgut, while infectious virions are released. The comprehensive demonstration of biocontrol is shown in Figure 1. These virions cause infection in epithelium cells of the midgut and start multiplying in the nucleus [10]. Further, these viruses are distributed in the body cavity and start infecting other tissues, i.e., tracheal matrix, adipose tissue, epidermal, even including Malpighian tube, salivary glands, and blood cells [94], which leads to its death after ingestion in 6 to 8 days compared to a healthy caterpillar; an infected one with nucleopolyhedroviral only eats 7% of food [94]. In *Baculovirus* infection, the main symptoms include yellowing of the skin, the appearance of blemishes, and a decrease in feeding [94]. Usually, infected larvae start moving upper parts and are attached to the plants in a hanging-down position upon their death, while some prolegs remain attached to plants [94]. Such larvae are soft with dark color and found with released body fluids rich in polyhedrons, aiding the further spread of the virus [94]. Virus efficacy and speed of killing FAW larvae depends on larva age at the time of infection, ingested virus amount, and its virulence with current climatic conditions, i.e., temperature, humidity, and solar radiation [95,96]. In addition to this, time of spray, equipment type, and formulations are influential in the efficiency of the virus [95,96].

3.2. Entomopathogenic Fungi

Entomopathogenic fungi (EPF) can infect several insect species on different stages at a wide range, causing epizootics under certain natural conditions [97]. 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 [97]. 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 [98]. Moisture has an important role for fungi as a biocontrol agent. Among the potentially beneficial fungi against insect pests, *Beauveria bassiana*, *Metarhizium anisopliae*, and *Nomuraea rileyi* are the most commonly used for *Spodoptera* control [98]. FAW larvae are susceptible to *B. bassiana* compared to other lepidopteran pests [99]. In vitro studies showed 30% and 87% mortality when *B. bassiana* and *M. anisopliae* was applied on second instars and eggs, respectively.

3.3. Entomopathogenic Bacteria

Bacillus thuringiensis (Bt) Berliner is one of the most widely used biopesticides for insect control [100]. These bacteria are Gram-positive, soil-dwelling bacteria that aid in producing crystal proteins known as delta-endotoxins, which are naturally insecticidal [101]. Only a few Bt products are effective against FAW available in the market for managing lepidopteran pests [101].

FAW has increased susceptibility to Bt *aizawai* and Bt *thuringiensis* [100] compared to Bt *kurstaki*, which is efficient against numerous lepidopteran pests [102]. There are few limitations in its wide adoption and use, including UV susceptibility of endotoxin, inability to reach pest for inducing toxin consumption, and the high cost of production [102]. Various research groups are trying to determine more effective Bt strains against FAW. In contrast, variation in susceptibility towards different Cyt toxins (also known as Cry toxins) has been observed among populations of FAW [103]. To control FAW, Bt-based biopesticides must be considered throughout the selection process in various locations. Seven Bt strains were highly effective among nineteen in screening against second-instar FAW larvae at ICIPE in Africa, causing 100% mortality within 7 days of post-treatment, having lethal time mortality (LT₅₀) with standard ranges of 2.33 ± 0.33 and 6.50 ± 0.76 days. Bt-based biopesticides have been considered for mass production through fermentation technology using solid-, semi-solid-, or liquid-state fermentation [104]. Not only Cry toxins, but also FAW show susceptibility towards vegetative insecticidal proteins that could be usually seen in Bt culture supernatants [105].

3.4. Entomopathogenic Nematodes EPNs

Entomopathogenic nematodes, i.e., *Steinernema feltiae*, *Steinernema carpocapsae*, *Heterorhabditis indica*, and *Heterorhabditis bacteriophora*, are used as effective biological control agents [106]. EPNs are eco-friendly and play an essential role in suppressing soil-dwelling insect pests, notably armyworms [106]. The susceptibility rate of FAW to such beneficial nematodes is 23,000 per sq. ft. to target mature and young larvae [10]. Early morning or late night are the most efficient times to apply beneficial nematodes because they are more active at these times and are less exposed to ultraviolet (UV) light, which helps them find armyworm larvae more easily [107].

In a petri dish, 280 infective juveniles of *Steinernema* sp. can kill 100% of third-instar FAW, while 400 infective juveniles of *H. indica* kill 75% of FAW [108]. Usage of hydraulic spraying jets, which require 100 filtrating mesh elements, could decrease the concentration of infective juveniles of *H. indica* and *Steinernema* species up to 28% and 53%, respectively [10]. The comprehensive demonstration of biocontrol is shown in Figure 1. Molina-Ochoa et al. [109] informed earlier that *S. carpocapsae* and *S. riobravis* efficiently manage FAW at the prepupal stage. According to various researchers, EPNs with resistant maize silk could increase FAW mortality at the prepupal stage [110]. These nematode species,

S. carpocapsae, *S. glaseri*, and *H. indica*, have shown compatibility with various commercial insecticides under laboratory conditions [110]. *Heterorhabditis indica* shows increased efficacy when mixed with lufenuron against FAW [111]. Moreover, a compatibility evaluation study of insecticides or biopesticides with EPNs is necessary before recommending it to use an IPM for FAW [111].

4. Botanical Pesticides

Local farmers have claimed that botanical extracts from local plants are beneficial [10]. Botanical pesticides are a better alternative to synthetic insecticides, which could be more harmful to the environment, increase consumer cost, and delay recovery [112–115] (Table 3). Such pesticides are also responsible for increased pest resistance [116–119]. Few botanical extracts include *Chrysanthemum cinerariifolium*, *Jatropha curcas*, *Nicotina tabacum*, *Milletia ferruginea*, *Phytolacca docendra*, and *Croton macrostachyus*, which could be used as insect pest control [120] (Table 3). Around 50 botanical pesticides were found to be registered for controlling FAW in more than 30 countries (Table 3). Among those, 23 are recommended for field trials and bioassays [2,121]. Solaris 6 SC[®] was shown to be the most effective insecticide against immature fall armyworms, followed by botanical extracts of garlic and neem, as well as detergent [10].

Botanical pesticides caused 80% mortality under laboratory conditions [122]. According to different reports and studies, these botanicals are effective against FAW [123,124] (Table 3). Neem extracts have shown 70% mortality in FAW [125,126]. *Eucalyptus urograndis* was found to be more helpful in saving maize from pests [124]. The seed powder of *Carica papaya* was discovered as an efficient chemical insecticide [127]. Neem oil containing 0.17–0.33% concentration reduces FAW damage in maize [123].

Botanical insecticides are target-specific, non-hazardous for the environment, and safe for natural enemies as compared to chemical pesticides [128]. Thus, their application promotes FAW natural parasitism up to 60% in comparison with pesticide-treated areas [41].

Table 3. Potential botanical pesticides against FAW.

Extract	Mode of Action	Species	Family	References
0.25% Neem oil	Larvicidal with up to 80% mortality in the lab	Neem: <i>Azadirachta indica</i>	Meliaceae	[122]
Hexane and ethanol extracts of seeds	Larvicidal with up to 100% mortality in the lab	<i>Aglaia cordata</i> Hiern	Meliaceae	[129]
Ethanol extract from seeds	Larval growth inhibition	<i>Annona mucosa</i> Jacquin	Annonaceae	[130]
Ethanol extracts from leaves	Ovicidal	<i>Vernonia holosenicea</i> , <i>Lychnophora ramosissima</i> , and <i>Chromolaena chaseae</i>	Asteraceae	[131]
Dichloromethane extracts of wood	Insect growth regulating (IGR) and larvicidal with up to 95% mortality	<i>Cedrela salvadorensis</i> and <i>Cedrela dugessi</i>	Meliaceae	[132]
Methanol extracts of roots and other aerial parts	Insect growth regulating (IGR), larvicidal, delayed pupation	<i>Myrtillocactus geometrizans</i>	Cactaceae	[133]
Essential oil from seeds	Affects spermatogenesis and, hence, egg laying	Long pepper, <i>Piper hispidinervum</i>	Piperaceae	[134]
Ethanol extracts of leaves	Antifeedant to larva; synergistic with pesticide	<i>Melia azedarach</i>	Meliaceae	[135]
Ethanol extracts of leaves	Antifeedant to larva; synergistic with pesticide	<i>Jatropha gossypifolia</i>	Euphorbiaceae	[135]
Castor oil and Ricinine (seed extracts)	Growth inhibition and larvicidal	<i>Ricinus communis</i>	Euphorbiaceae	[136]

(Source: adopted from *Fall Armyworm in Africa: A Guide for Integrated Pest Management*).

A recent study conducted in Ghana recommends farmers to use intercropping technique during the first nine weeks of crop establishment because foliage of a crop remains too soft for FAW neonates; therefore, moths are attracted by crop to lay eggs [137]. Under this duration, intercropping encouraged natural biological control agents to establish under the prevailing conditions. It resultantly checked the FAW population [13]. Push–pull technology (PPT) is now suggested for FAW management [36]. International Centre of Insect Physiology and Ecology (ICIPE) introduced this method to control stem borers in maize. The push–pull technology comprises intercropping maize with drought-tolerant greenleaf *Desmodium intortum* (Mill.) Urb., while *Brachiaria* cv Mulato II is planted as a border crop surrounding the intercrop. *Desmodium* plays an important role in protecting maize crops by repelling moths away with the emission of semiochemicals [16]. At least 80% of FAW infestations can be eliminated using this technique [16,36]. In Uganda, FAW infestation levels on maize using PPT were 36–38%, compared to 95% when single cropping was used. PPT is better than maize-legume intercropping for controlling FAW infestation [138]. Botanical or biopesticides are recommended as an alternative to hazardous synthetic insecticides, such as pyrethroids and organophosphorus compounds, which can influence and interfere with environmental conditions, and increase expense, resurgence, and insect resistance.

Because of their low cost and accessibility, farmers and growers in developing countries use botanical, eco-friendly, sustainable techniques to manage insect pests of field crops and stored goods. *Milletia ferruginea*, *Azadirachta indica*, *Croton macrostachyus*, *Jatropha curcas*, *Phytolacca docendra*, *Chrysanthemum cinerariifolium*, and *Nicotina tabacum* extracts have been exploited successfully against insect pests [139]. *Azadirachta indica* seed extract causes the highest mortality in FAW at the larval stage [126]. Martínez et al. [140] discovered that the *Argemone ochroleuca* causes FAW mortality by reducing feeding behavior and stunting larval growth. Various botanical plant extracts could increase insecticidal efficiency against FAW [141]. Several products, such as extracts of *Azadirachtin* from neem and pyrethrins from pyrethrum, have been successfully commercialized, while others, such as those based on garlic, ryanodine, quassia, nicotine, and rotenone, have been registered worldwide [142]. Commercial products are available under different formulations and mode of action, applied diluted with water or sprayed with chemical insecticides and dust formulation. Furthermore, there are difficulties in application mode, such as neem-based solutions having high photosensitivity for *Azadirachtin*, resulting in a lower residual impact in fields due to sunlight exposure [122]. The comprehensive demonstration of biocontrol is shown in Figure 1. Few botanicals, including neem (*Azadirachta indica*), pyrethrum (*Tanacetum cinerariifolium*), fish-poison bean (*Tephrosia vogelii*), wild sage (*Lantana camara*), West African pepper (*Piper guineense*), wild marigold (*Tagetes minuta*), onion (*Allium sativum*, *Allium cepa*), tobacco (*Nicotiana* sp.), chilies (*Capsicum* sp.), lemongrass (*Cymbopogon citratus*), chrysanthemum (*Chrysanthemum* sp.), wild sunflower (*Tithonia diversifolia*), acacia (*Acacia* sp.), jatropha (*Jatropha curcas*), and Persian lilac (*Melia azedarach*), have good insecticidal properties in managing stemborers in Africa [143–145].

5. Conclusions

Spodoptera frugiperda is a worldwide invasive pest, causing significant losses in host crops. FAW comprises two genetic strains: the “rice strain”, which prefers rice and other grass species, and the “maize strain”, which feeds primarily on maize and occasionally on sorghum. Small and marginal farmers that lack the financial resources to purchase chemical pesticides or expensive seeds are more likely to benefit from potential control methods. Maintaining natural antagonist diversity and intensity is crucial for biological control strategies. It may be accomplished by providing favorable conditions for biological control agents near crops. Shelter crops, alternate food resources, and multiplication favoring environments for such biological species are all important steps in regulating the population of FAWs. Growing Mexican sunflower or *Crotalaria* on crop edges in maize-growing areas is a good way of boosting beneficial insect biodiversity, even if they are not related to FAW, and achieve landscape management goals. The push–pull technology

(PPT) intercropping is also beneficial against pests to repel them out of fields. In addition, economic injury levels (EIL), observation through surveys, and pest management efforts might be used to evaluate biocontrol-based IPM applications against FAW.

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