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Comprehensive strategies for the integrated management of fall armyworm: a focus on biocontrol, cultural, and chemical methods

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ABSTRACT

Spodoptera frugiperda, are polyphagous agricultural pests that began in America and were ultimately discovered in West Africa in 2016.The larval stage of the pest's life cycle causes the most damage. It impacts 353 different crop types and leads to a 70% loss in crop yield, hurting the economy. Studies have shown that these pests do well in temperatures above 10°C, but moth wings become deformed when the temperature goes above 30°C.The cultural method is the most effective pest control approach, making up 56% of pest management efforts. The push and pull technique, meanwhile, controls 82.6% of larvae per plant. Research has found that Azadirachta indica (neem) seed powder can reduce larval mortality by 70%, while L. javanica and N. tobacum decrease larval toxicity by 66%. Spinosad causes over 90% of larval deaths, while a mixture of sawdust and chlorpyrifos controls 20% of the pests. This detailed review covers all types of biological control methods, including parasitoids, nematodes, predators, viruses, entomopathogenic fungi, biopesticide bacteria, as well as cultural, chemical, physical, and botanical controls. It focuses on how effective these methods are against the Fall Armyworm (FAW).

Güz tırtılının entegre yönetimi için kapsamlı stratejiler: biyokontrol, kültürel ve kimyasal yöntemlere odaklanma

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ÖZET

Spodoptera frugiperda, Amerika'da başlayan ve son olarak 2016'da Batı Afrika'da keşfedilen polifag tarım zararlısıdır ve zararlının yaşam döngüsünün larva aşaması en fazla zarara neden olur. 353 farklı ürün türünü etkilemekte ve ürün veriminde %70'lik bir kayba yol açarak ekonomiye zarar vermektedir. Çalışmalar, bu zararlıların 10°C'nin üzerindeki sıcaklıklarda iyi performans gösterdiğini, ancak sıcaklık 30°C'nin üzerine çıktığında güve kanatlarının deforme olduğunu göstermiştir.Kültürel yöntem, haşere yönetimi çabalarının %56'sını oluşturan en etkili haşere kontrol yaklaşımıdır. İtme ve çekme tekniği ise bitki başına larvaların %82,6'sını kontrol etmektedir. Araştırmalar, Azadirachta indica (neem) tohum tozunun larva ölümlerini %70 oranında azaltabildiğini, *L. javanica* ve *N. tobacum'un* ise larva toksisitesini %66 oranında azalttığını ortaya koymuştur. Spinosad larva ölümlerinin %90'ından fazlasına neden olurken, talaş ve klorpirifos karışımı zararlıların %20'sini kontrol etmektedir. Bu ayrıntılı inceleme, parazitoidler, nematodlar, predatörler, virüsler, entomopatojenik mantarlar, biyopestisit bakteriler ve kültürel, kimyasal, fiziksel ve botanik kontroller de dahil olmak üzere her türlü biyolojik kontrol yöntemini kapsamaktadır. Bu yöntemlerin Güz Ordusu Kurduna (FAW) karşı ne kadar etkili olduğuna odaklanmaktadır.

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1.Introduction

Fall armyworms (*Spodoptera frugiperda* (J.E. Smith) is one of the most damaging insect pests in the family Noctuidae. This pest has polyphagous which can damage a variety of vegetable crops as well as commercially valuable cereal crops like cotton, corn, sorghum, rice and eventually have an impact on food security (Barbosa et al., 2018). The FAW consumes plant species' stems, leaves and reproductive organs. It is common to the Americas' subtropical and tropical climates. One of the most prevalent pests of maize in North and South America is FAW, which first emerged in America. As of the end of 2017, it had spread to over 30 countries in tropical and southern Africa, including Cabo Verde, Madagascar, and the Seychelles, making it one of the most invasive pests on the continent. It was first documented in Africa in 2016 (Sisay et al., 2018). Almost 353 plants have been recognized as this pest's hosts. The first symptoms appear when the larval stage creates various-sized papery windows in the leaves, which causes significant plant defoliation and an accumulation of feces. Later on, the growth and growth of the plants is impacted (Reddy, 2019). The FAW is a harmful pest; if prevention strategies are not implemented, CABI (2017) estimates that the bug may cost African nations 6.1 billion US dollars in revenue loss. FAW travels about 500 miles before starting to place egg (Prasanna et al., 2018). Until they reach adulthood, a single generation of FAW moths can disperse over 500 kilometers from the site of emergence because of wind (Kumar et al., 2022). The assessment of crop varieties that can resist Fall Armyworm (FAW) should start. Over time, national policies should support safer pest control solutions by providing temporary subsidies, quickly evaluating and registering biotechnology, biological control products, and insecticides. For farmers without the financial means to buy costly crops and chemical insecticides, biological control methods are more appropriate (Ratto et al., 2022). There are microbial formulations on the market that are effective in agricultural systems and originate from illnesses and arthropod natural enemies. Since microbial formulations are mostly bulk produced in liquid media, their production costs have fallen significantly (Mahmoud et al., 2017). Control failures arise from the FAW caterpillar's larvae being firmly buried in the corn ears and leaf curls. But it only comes during the night or at dawn and twilight to eat on plants. The article covers vital information of the fall armyworm's introduction, identification, and possible control measures.

2. Taxonomy of Fall armyworm

There are two fall armyworm strains, such as the ones found in rice and corn strains (Nagoshi et al., 2018). As the corn strain consumes corn, cotton, and sorghum, the rice strain feeds on rice and other grazing grasses. Although sharing a similar morphology, these strains can be separated molecularly. In comparison to the fall armyworm present in America, which possess both strains, the invasion in Africa has greater diversity (Jacobs et al., 2018). The armyworm belongs to domain is Eukaryote, phylum Arthropoda, class Insecta, order Lepidoptera, family Noctuidae, genus *Spodoptera.*

3. The economic value of FAW

The most harmful and destructive stage of the fall armyworm life cycle for crops is the larval stage. FAW larvae infected maize plants can be observed on various plant components like leaf whorls, young leaves, cobs, and tassels depending on the plant's growth stage (Goergen et al., 2016). In estimating the loss resulting from FAW, several factors must be considered. In general, the quantity of pests, the timing of infestation, the pest's natural competitors and pathogens at that particular moment, and the crop's nutritional and moisture status together play a role in crop infestation (Sagar et al., 2020). There is an 11.57% reduction in yield in maize when the insect incidence varies from 26.4% to 55.9%. The yield decreases 58% by 25–50% damage to the leaf, silk, and tassel, whereas up to 73% of the crop's yield is lost by 55–100% severity during the mid–late whorl stage (Chimweta et al., 2019). During the reporting period, there was an output loss of 30.54 million tons in Ethiopia, 13.91 million tons in Uganda, and 3.2 million tons in Tanzania. Fall armyworm impacted 250,000 hectares of agricultural land in Kenya, which makes up 11% of the nation's total area under corn cultivation. In a similar vein, FAW estimated that maize loss in output in Zambia and Ghana was 40% and 45%, respectively. If control measures hadn't been implemented, losses from FAW in twelve African countries including Ghana and Zambia were estimated to be between 8.5 and 21 million tons, or approximately 250–630 million US dollars (Bateman et al., 2018). According to research, FAW has impacted 170,000 hectares of maize harvests across 10 states in India. This pest mostly affects Yunnan province in China, where it has been recorded to damage 80,000 hectares of land and crops comprising maize, ginger and sorghum. In China, 11,1992.17 ha of the total area have been harmed, maize covers 98.6% of the total area (FAO, 2019). FAW infestations are reported in Bangladesh, Indonesia, Myanmar, and Vietnam, affecting land areas ranging from 0.5% to 32%. Thailand is experiencing a 25-40% yield loss, resulting in a loss of 130-260 million dollars. The fatal pest can have an enormous effect on Nepalese farmers and the country's economy because of its constant appetite for crops like maize and others. Since the climate in Nepal is favorable to the formation of populations of this insect, crop loss in maize of up to 100% will be expected if this pest is not managed (Beshir et al., 2019).

4. Favorable environment for their developments

Climate impacts fall armyworms, and variations in weather conditions can have an effect on the armyworm's distribution over different geographical areas. According to reports, the state of the environment has an important effect on several traits, like death, growth, survival and abundance (Ramirez et al., 2017). The larger invasion of FAW is controlled by the pest overwintering mechanism. It grows best in cool, humid temperatures and during severe outbreaks following periods of heavy rain (Sharma et al., 2022). A warm, muggy growing season with lots of rain is ideal for the pest's growth and survival. At temperatures below ten degrees Celsius, the bugs stop growing. More than ten generations of fall armyworms occur annually in tropical and subtropical regions, compared to just two in temperate regions, suggesting that these regions are better suited for the species' efficient reproduction.

5. Distribution pattern

In an adult stage, it can fly longer and cover an area of about 300 miles. The movement of air in weather fronts could be the cause of this high migration rate. The most prevalent insect pest in tropical America is the fall armyworm, which is common in both tropical and subtropical areas of the nation. By the end of 2016, it initially emerged in West Africa and quickly spread to Sub-Saharan Africa (SSA), where it was subsequently confirmed in 44 African nations (Sisay et al., 2019). According to the research, both FAW strains invaded Africa from the Americas through cargo containers, commercial flights, or airplane holds. From there, they dispersed via wind (Day et al., 2018). Fall armyworm, first reported in Karnataka, India in 2018, has spread to various Asian regions including West Bengal, Odisha, Maharashtra, Gujrat, Bihar, and Chhattisgarh (CABI, 2020). The insect problem has been experienced by various Asian nations, including Japan, China, Cambodia, Bangladesh, Myanmar, Indonesia, Thailand, Korea, Sri Lanka, Vietnam, and China (FAO, 2019). Fall armyworm outbreaks in Nepal have been reported in 15 districts, posing a significant risk of rapid spread, despite not being reported globally.

6. Fall armyworm damage symptoms in maize

As soon as the eggs hatch, maize gets infected with Fall armyworm. The most common signs of FAW are papery windows on leaves that can range in size, have jagged edges, and seem oblong to spherical. These leaves can also become loose and separated from the plants. Due to the larval instars' ravenous feeding habits, major defoliation and an abundance of feces remaining on the plant are visible during the severe stage. Crop growth and development eventually stop, which prevents the development of cobs and tassels (Reddy, 2019). Larger, elongated holes appear from the third to the sixth instar of the infestation, while translucent patches are seen in the window glass during the first and second stars. In the end, the Fall armyworm feces appear on the leaves or in the maize funnels as sawdust-like particles (CABI, 2018). The crop's leaf damage can be evaluated using the methods (Table 1).

Table 1. Scale for evaluating crop leaf damage caused by fall armyworm (*S. frugiperda*)

Scale	Damage
0	No obvious damage to the leaves
1	Leaves with only tiny holes damaged
2	Leaf damage from pinholes and bullet wounds
3	1-3 leaves with tiny, elongated lesions (5–10 mm)
4	Lesion of a moderate size (10–30 mm) on 4–7 leaves
5	Large, elongated lesions (more than 30 mm) or little bits ingested on three to five leaves
6	Large parts consumed on 3-5 leaves and elongated lesions (>30 mm) are observed.
7	50% of the leaf eaten and elongated lesions (>30 cm).
8	Long (30 cm) lesions and significant eating pieces on 70% of the leaves.

7. Life Cycle Stages of Fall Armyworm

There are four distinct stages in *S. frugiperda*'s life cycle (Figure 1). The Fall armyworm can be identified by its physical characteristics, unique indications of damage on vulnerable crops, or molecular characteristics (FAO, 2019).

Egg Stage: The fall armyworm's egg is 0.4 mm in size and 0.3 mm in length, and it has a dome-like, flattened base. The creamy white eggs of the fall armyworm have reticulated ribs that are encased in abdominal hairs. The female lays a large batch of eggs, 100–200 at a time (Prasanna et al., 2018).

Larvae Stage: The fresh-hatched caterpillars are green during their first and second stars, then turn brown or black between their third and sixth instars (CABI, 2018). The mature larva has four dark elevated spots that create squares on its rough or granular epidermis, and it has a white inverted "Y"-shaped mark on the front. The head capsules of the 1-6 instar measure 0.35, 0.45, 0.75, 1.3, 2.0, and 2.6 mm in width, while the body lengths range around 1.7, 3.5, 6.4, 10.0, 17.2, and 34.2 mm, in that sequence.

Pupae Stage: Pupae are oval reddish brown and form a 20–30 mm long cocoon. They are typically found in soil that is 2–8 cm deep (CABI, 2018). Pupae are typically found in soil in cocoons that are 20–30 mm broad and 15 mm long (Silva et al., 2017).

Adult Stage: Adult Fall armyworm members display nocturnal behavior (CABI, 2017). The mature moths' range in size from 32 to 40 mm according to the color. The forewings of the male moths are dark and shaded, with triangular white patches near the center of the wing and at its tip (Assef & Ayalew, 2019). Because they are migratory, the moths can fly over long distances.

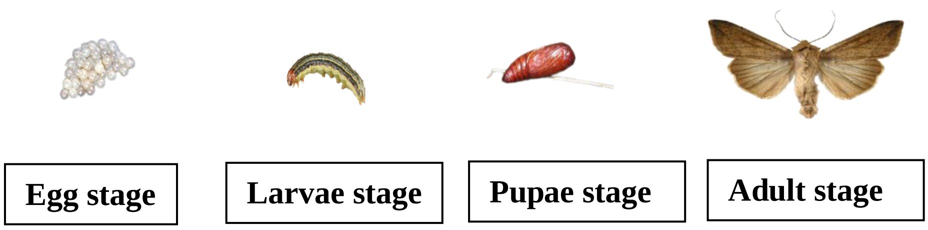

Figure 1. Life cycle stages of Fall armyworm

8. Integrated Management of Fall Armyworms

Fall armyworms pose economic threats to pets, and control techniques should be applied in maize only if 20% of whorls are infested or 5% of seedlings are clipped (Fernandez, 2002). The fall armyworm larval stage is the ideal period to properly control the pest; choosing an appropriate time of day to complete the management task is crucial (Assefa & Ayalew, 2019).

Consultancy services: A variety of methods of communication are needed in the private as well as public sectors, depending on the information that needs to be shared and the control strategies that are being maintained (Day et al., 2017; Azeem et al., 2020). The control of the fall armyworm starts with this, which is also the most important stage. Asian nations like Sri Lanka, Indonesia, Bangladesh, Myanmar, Japan and China are implementing this strategy to inform the public on the control of the destructive pest (FAO, 2019).

Mechanical and physical approach: Mechanical and Physical management is the most effective and rapid way to manage biological pests (Ali et al., 2021a). One method of controlling fall armyworms is the hand collecting and destruction of egg masses, as well as the mass crushing or soaking of neonate larvae in kerosene water (Firake, 2019). Another stated method of control is to apply dry sand into the whorl of afflicted maize plants as soon as FAW incidence appears in the field. Because the fall armyworm eggs and caterpillars are rare, hand-picking and smashing them can be a useful precaution for tiny gardens or a few impacted plants. 54% of insect control has been discovered to be accomplished by using mechanical management control (Assefa, 2018). To reduce the incidence of the fall armyworm, pheromone traps installed at a rate of five per acre at probable spreading areas are used throughout the crop season and off-season (Firake, 2019). For scaling, the pheromone traps that draw the male armyworm moths are suggested because of their ease of use (FAO, 2017). To catch fall armyworm moths, a traditional bucket trap featuring a yellow funnel, white bucket and green canopy has proven to be the most effective (Hardke et al., 2015).

Chemical approach: Chemical control is the best and fastest method to control biological pests and pathogens (Naqvi et al., 2024). The treatment of the fall armyworm greatly depends on the timing of the chemical application. The individual should be aware of the life cycle and the best times to administer pesticides, such as during the day when spraying is ineffective and when the larvae are deeply rooted in the maize whorls and ears because larvae only emerge at dusk, night or dawn to feed on plants (Day et al., 2017). It has been suggested to use a variety of pesticides to control fall armyworms. Various pesticides, including methyl parathion, methomyl, pyrethroids, organophosphate insecticide, and cyfluthrin can be employed to control fall armyworms (Badhai et al., 2019). It was discovered that the application of cyantraniliprole and chlorantraniliprole as a seed treatment was efficacious in mitigating the fall armyworm infestations in soy (Sharma et al., 2022). 20% control of the fall armyworm was observed when sawdust and chlorpyrifos were combined and applied as a therapy. In order to suppress the fall armyworm, chemicals such as beta cypermethrin, carbosulfan, emamectin benzoate, cartap hydrochloride, and chlorpyrifos have been applied extensively throughout Africa. Among these, using beta cypermethrin, cartap hydrochloride, and emamectin benzoate on vegetables is also recommended (IRAC South Africa, 2018). Since threshold levels are not being utilized to assess whether pesticides are necessary, there is the worry that using chemical controls improperly could result in the emergence of resistance in plants, harm to those plants, and hazards to the environment and public health. Foliar sprays against FAW in soya were not as necessary when seed treatments with chlorantraniliprole and cyantraniliprole were used (Sharma et al., 2022). FAW was not affected by soil treatment in Nicaraguan tests. Smallholder farmers in Ethiopia and Kenya use dry sand and trichlorfon mixtures, which are applied to the whorls using a plastic bottle and are thought to be effective (Kumela et al., 2017). In contrast, mixtures of sawdust and chlorpyrifos decreased the amount of pesticide required by 20% without sacrificing control. Spinosad and the novel insecticides spinetoram chlorantraniliprole and flubendiamide have been shown to outperform the conventional insecticides lambda-cyhalothrin and novaluron, resulting in over 90% decreases in larval morality (Hardke et al., 2015).

Cultural approach: Fall armyworm is frequently controlled by applying chemical or synthetic pesticides (Assefa et al., 2019). Using various cultural techniques, however, can lessen the amount of crop loss resulting from FAW. It is an effective pest management plan for FAW must include cultural control. Preventing ear damage caused by FAW and other insects involves growing maize hybrids with tight husk covers, balanced fertilizer use, and clean cultivation (Kumela et al., 2017). Applied as granules or powder into the whorls, the dry mixture of sand and trichlorfon has shown to be a popular and effective method among small-scale farmers in Ethiopia and Kenya. Crop leftovers that are left in the field can be destroyed by burning them, rotating the crop, selecting an appropriate variety, keeping high soil tilth, and regularly checking the field (Sharma et al., 2022). Systems that grow mainly maize provide a favorable setting for FAW to expand quickly. Chemical and cultural control techniques can be used to manage armyworms. Avoiding late planting is part of the cultural control since the ears of maize would be more severely damaged by a larger FAW infestation than those of the early plantings. In order to reduce the invasion of FAW, it may also be helpful to intercrop and rotate maize with non-host crops such as beans and sunflowers (FAO, 2018). The majority of subsistence farmers in Africa also don't use pesticides on their maize crops, but they do employ cultural control techniques that either kill or discourage pests, like hand-picking caterpillars and applying wood ashes and soils to leaf whorls (Ratto et al., 2022). According to a survey done in Ethiopia and Kenya, 14% and 39% of the farmers, respectively, used traditional techniques (such as handpicking) to manage FAW (Kumela et al., 2017). Up to 54% of farmers using a mechanical approach are able to control the pest.

9. Biological Approaches to control the FAW

Microorganism: Entomopathogens are pathogen-causing organisms that infect and cause diseases in insects. They include fungi (*Metarhizium anisopliae* and *Beauveria bassiana*), bacteria (*Bacillus thuringiensis*), protozoans, nematodes, viruses and other well-known recognized as being against FAW management.

Entomopathogenic fungus: Fungal antagonists play a significant role in controlling plant pathogens and destructive pests (Ali et al., 2021b; Tabbasum et al., 2022). Entomopathogenic fungi (EPF) can cause epizootics in particular natural habitats by infecting a range of insect species at different stages throughout a large range (da Silva et al., 2020). Fungal spores infect EPF species by first multiplying inside the insect's body through the integument. Certain poisons released by EPF cause tissue destruction, and the insect eventually perishes after multiplying. The climate and the frequency of insect contact dictate when the epizootics are introduced (da Silva et al., 2020). Insects with EPF infection turn green, cream, brown, or reddish in appearance, cease feeding, and eventually die as a hard, calcareous cadaver where the fungus starts to sporulate (Jaiswal et al., 2020). Moisture has a major impact on the biocontrol activity of mushrooms. *Metarhizium anisopliae*, *Nomuraea rileyi*, and *Beauveria bassiana* are utilized most frequently to control *Spodoptera* among the fungi that may be advantageous against insect pests (Jaiswal et al., 2020). When it comes to lepidopteran pests, FAW larvae are more susceptible to *B. bassiana*. Applying *M. anisopliae* to second instars and *B. bassiana* to eggs resulted in 87% and 30% mortality, respectively, according to in vitro investigations.

Entomopathogenic Bacteria: Bacillus genus members are commonly used as biopesticides to control plant diseases and insect pests (Ali et al., 2022; Ali et al., 2023b; Ali et al., 2024). *Bacillus thuringiensis* (Bt) Berliner is one of the most commonly used biopesticides for insect control (Kanedi et al., 2023). These bacteria as soil-dwelling, gram-positive bacteria that aid in the synthesis of crystal proteins called delta-endotoxins, which have an insecticidal impact. For controlling lepidopteran pests, only a small number of Bt treatments that are sold in the market are effective against FAW (Bortoli et al., 2019). In comparison to Bt *kurstaki*, which is efficient against a variety of lepidopteran pests, FAW is more susceptible to Bt *thuringiensis* and Bt *aizawai* (Silva et al., 2020). Its widespread adoption and application are occasionally limited by factors such as the endotoxin's UV sensitivity, the high cost of manufacture, and the inability to reach the pest to induce toxin intake (Silva et al., 2020). Several research teams are attempting to identify Bt strains that are more effective against FAW. Conversely, populations of FAW have been found to differ in their susceptibility to various Cyt toxins, which are also referred to as Cry toxins. Throughout the selection process in many places, biopesticides based on Bt must be taken into consideration in order to manage FAW. Lethal time mortality (LT50) with standard ranges of 2.33 ± 0.33 days and 6.50 ± 0.76 was caused by seven Bt strains that were highly effective against nineteen second-instar FAW larvae at ICIPE in Africa. These strains also caused 100% death within seven days of treatment. Large-scale manufacturing of Bt-based biopesticides has been explored through fermentation technology, employing either solid- or semi-solid fermentation processes (Thiviya et al., 2021). Vegetative insecticidal proteins, the majority of which are present in Bt culture supernatants, are likewise sensitive to cry toxins, as demonstrated by FAW.

Entomopathogenic Nematodes (EPNs): As effective biological control agents, entomopathogenic nematodes such as *Steinernema feltiae, Steinernema carpocapsae, Heterorhabditis bacteriophora,* and *Heterorhabditis indica* are employed. EPNs are beneficial to the ecosystem and play a significant role in managing pest insects that live in the soil, such as armyworms (Dillman et al., 2019). FAW has a 23,000 sensitivity rate to beneficial nematodes, targeting immature and adult larvae. Applying them early or late at night is optimal due to UV light sensitivity (Prasanna et al., 2018; Shapiro et al., 2018). In a petri dish, 400 infectious juveniles of *H. indica* kill 75% of FAW, but 280 infectious juveniles of *Steinernema* sp. can kill 100% of third-instar FAW (Shamseldean et al., 2024). Hydraulic spraying jets, which need 100 filtrating mesh elements, can reduce the concentration of infectious juveniles of *H. indica* and *Steinernema* sp. up to 28% and 53%, respectively. At the prepupal stage, *S. riobravis* and S*. carpocapsae* effectively control FAW. Several scientists claim that EPNs with resistant maize silk may increase FAW death during the prepupal phase. Under lab settings, these three nematode species, *S. glaseri*, *H. indica*, and *S. carpocapsae* have demonstrated compatibility with several pesticides. *H. indica* is more efficient against FAW when combined with lufenuron. Moreover, before advising the use of an IPM for FAW, a compatibility assessment of biopesticides with EPNs is necessary (Roby et al., 2023).

Botanicals: Plants are quite a safe and eco-friendly way to control the plants' pests (Ali et al. 2020). For the management of FAW, a few biocontrol agents have been proven to be successful. Multiple natural enemies can be built up through habitat management, which also protects natural enemies in-situ and increases plant diversity through intercropping with pulses and beautiful flowering plants (Firake, 2019). *Bacillus thuringiensis* var *kurstaki* can be applied at a rate of 2 g per liter (or 400 g per acre) to effectively manage FAW. It is advised to apply *Metarhizium anisopliae* (1x108 cfu/g) talc formulation at a rate of 5g/liter whorl 15–25 days after sowing. Similarly, it has been reported that 1or 2 sprays at the interim of 10 days apart, depending on the level of pest damage, effectively prevent the spread of the pest infection. The use of biopesticides particularly based on the fungi (such as *Beauveria bassiana*), and bacteria such as *Bacillus thuringiensis* (Bt) have been efficiently used for the management of FAW (FAO, 2018). To decrease leaf defoliation in crops these biotic agents also contribute. Arthropod bio-control agents and several microbial pathogens have been effectively used for the management of FAW (Pilkington et al., 2019). Fall armyworm can be effectively controlled by 53 species of parasites representing 43 genera and 10 families found worldwide (Assefa, 2018). The *Beauveria* isolate caused 30% of the mortality of second instar larvae, whereas the *Metarhizium* isolate was responsible for 87% of the mortality of egg and 96.5 % of the mortality neonate larvae in the assessment of the effectiveness of entomopathogenic fungus against and second instar larvae and eggs. Numerous lepidopteran insects of the noctuidae family can be effectively controlled by a variety of natural enemies (Aktuse et al., 2019). Several insect pests may be biologically managed by these natural enemies. Fall armyworm infestation was reported to be well controlled in Ethiopia by the larval parasitoid *Cotesia icipe*; in Kenya, the pest was found to be managed by *Plaexorista zonata* (Sisay et al., 2018). Numerous species of parasites from the Telenomus and Trichogramma families, which are easy to raise in a laboratory are widely used to control fall armyworms (Tefera, 2019). Regarding the management of FAW, the biological control agents were reported are *C. insularis*, *C. marginiventris*, *Telenomus remus* (Platygastridae), *Archytas*, earwigs (Dermaptera), *Lespesia* (Tachinidae), Ladybird beetles (Coccinellidae*), Trichogramma* spp., (Braconidae), *Podisus* (Pentatomidae), *Nabis* (Nabidae), Geocoris (Lygaeidae), Assassin and flower bugs like *Zelus* (Reduviidae), *Anthocoris* (Anthocoridae), ants, birds, batsand minute pirate bug (orius insidiosus) (FAO, 2018).

Plants Extracts: It is advised to utilize botanical pesticides instead of dangerous synthetic insecticides like pyrethroids and organophosphorus, which can cause environmental disruptions, increase user costs, pest resurgence, and pest resistance to insecticides (Ali et al., 2023a; Sowmiya et al., 2024). Farmers in developing nations have been using botanical pesticides for centuries to control insect pests of stored goods and field crops due to their affordability and availability (Schmutterer, 1985). These tools are safer and more environmentally friendly than other methods. *P. docendra*, *J. curcas*, *N. tabacum*, *M. ferruginea*, *A. indica*, *C. macrostachyus*, and *C. cinerariifollium* are just a few of the many botanicals that have been effectively employed to manage insect pests (Rizqullah et al., 2023). A*. indica* seed cake extract found significant larval mortality of FAW (Silva et al., 2020). Ethanolic extracts of *A. ochroleuca* (Papaveraceae) reduced feeding and retarded larval growth, which resulted in FAW larval death. Although many other plants have been commercially commercialized, only a small number of them exhibit insecticidal action against FAW in extracts (Junitor et al., 2021). In Latin America, azadirachtin (derived from neem) and pyrethrins (from pyrethrum) are the most commonly utilized products. Global product registrations have been made for a few items including rotenone, garlic, nicotine, rianodine, quassia, and other extracts (Kasoma et al., 2020). Neem-based sprays face challenges due to the high photosensitivity of azadirachtin and the lack of quality control. The short residual life of neem in field settings and lack of standardization impact insecticide effectiveness. Testing neem extracts may not be suitable for conventional pesticide efficacy due to low caterpillar mortality (Viana and Prates, 2003; Junitor et al., 2021).

Parasitoid and Predators: There are roughly 150 species of parasitoids known, originating from various parts of the Americas and the Caribbean (Table 2). The *S. frugiperda* larvae and eggs contain 53 distinct species of parasitoids, such as *Apanteles marginiventris, Chelonus insularis, Ophion spp,Campoletis grioti, Ternelucha spp., Rogus laphygmae, Meteorus autographae,* and *Ephisoma vitticole* (Adjaoke et al., 2023). Over 44% of naturally occurring parasites have been found in American non-sprayed fields (FAO, 2017). A level of 45.3% parasitism was shown by these species (Sisay et al., 2018). To manage *S. frugiperda*, three predator species and seven parasitoids' species were found in Ghana (Koffi et al., 2020). The three species of predators include *Pheidole megacephala F., Haematochares obscuripennis (Stal), Peprius nodulipes (Signoret)*. These seven parasitoid species are listed as *M. testacea, C. icipe, Bracon* sp.*, Anatrichus erinaceus (Loew), tachinid fly (Diptera: Tachinidae), C. luteum* and an uncertain *C. bifoveolatus* (Koffi et al., 2020). The degree of parasitism and species occurrence vary by region (Kenis et al., 2019). This finding is based on type changes crop stage, geographic regions, and agronomic methods (Hay-Roe et al., 2016). It has been observed that *Coccygidium luteum* from Tanzania and Kenya can cause up to 9 to 19% parasitism in *S. frugipera* (Sisay et al., 2018). In America, mass breeding and the introduction of parasitoids and predators have been employed to manage other pests to reduce the growing *S. frugiperda* pest population (Kumar et al., 2022). Sub-Saharan Africa's government uses classical biocontrol to manage *S. frugiperda* because it is a costly method (FAO, 2018). Native parasitoids with a greater level of parasitism have been found in many SSA communities (Agboyi et al., 2020). Releasing predators to combat the growing FAW pest population and utilizing augmentative biocontrol is the most effective approach to managing FAW (FAO, 2018). In America, *S. frugiperda* eggs have been effectively managed with the application of *trichogramma* parasitoids (Prasanna et al., 2018). *Telenomus* and *Trichogramma* are parasitoids that effectively enhance biocontrol against *S. frugiperda* (Agboyi et al., 2020). Parasites (*Trichogramma* and *Telenomus*) are inserted into maizefields before the FAW neonates emerge, to control the FAW population during the egg form. Upon finding FAW egg masses, these parasitoids lay their eggs on them (CIPE, 2018). Lepidopterous species found in Africa that have been parasitized by *C. luteum* include *Prophanti ssp. Spodoptera exempta* (Walker), *Condica capensis* (Guenée), *Crypsotidia mesosema* (Hampson), and *Spodoptera exigua* (Hübner) (Van et al., 2019). In Africa and many other countries *Coccygidium luteum* has been reported, such as Madagascar, Kenya, Guinea, Nigeria, Ethiopia, Namibia, Mauritius, Congo, Tanzania, Uganda, Somalia, South Africa, Cameroon, and Rodrigues Island (Agboyi et al., 2020). *Coccygidium luteum*, which has more than 46 species, is a solitary koinobiont parasitoid that is a member of the Braconid subfamily Agathidinae (Ganou et al., 2024). The efficiency of *Agathidinae* species in this subfamily as biocontrol agents against insect pests is poorly understood, and their effectiveness is rarely investigated (Abbas et al., 2022). In China, *C. luteum* regulates the eggs of numerous species of *Spodoptera* (Tang et al., 2019). Parasitoids may complete several generations in 90 days, which has caused early maturing maize types to proliferate in West Africa (Oluwaranti et al., 2018). Populations of natural enemies are affected by variations in parasitism (Abbas et al., 2022). Levels of parasitism were lower on average than previously reported levels in the United States i.e., 35%, 15.5%, 28.3%, 8.1%, 13.8% and 18.3%. From the several localities of Benin and Ghana 10 different species of parasitoids was reported (Agboyi et al., 2020). These species are *Charops spp, Drino quadrizonula* (Thomson), *Trichogramma spp. Meteoridea cf*, *Telenomus remus*, *Pristomerus pallidus* (Kriechbaumer), *Coccygidium luteum*, *Metopius discolour* (Tosquinet), *Cotesia icipe* and *Chelonus bifoveolatus* (Szpligeti) (Agboyi et al., 2020).

Table 2. Predators against FAW

Predator	**Family**	**Description**	**Reference**
Spined soldier bug	Pentatomidae	Nymphs and adults primarily prey on the larvae of lepidopterans. It punctures the spined soldier insect, *Podisus maculiventris Pentatomidae Heteroptera*, bites its victim and quickly impairs it with a toxin. The predator killed the prey by sucking its internal fluids.	Kneeland et al. (2020)
Pirate bug	Cimicoidea	A significant parasite. Aphids, tiny *Lepidoptera* larvae, and moth eggs are all food sources for *O. sauteri*.	Jaraleno et al. (2020)
Assassin bug	Reduviidae	In maize, the most prevalent killer insect genus is Zelus. Clusters of eggs are produced by females on plant leaves or even the ground. The nymphs resemble adults and lack feathers.	Grundy et al. (2019)
Ground beetle	Carabini	The females lay their eggs on the soil's surface or slightly below it after mating before the ground pupation. The immature stage has three instars.	Rukundo et al. (2020)
Flower bug	Anthocoridae	Most species utilized in biological control operations are extremely abundant ones. They feed on lepidopteran eggs, aphids, thrips.	Pathrose et al. (2023)

Use of plant-based Pesticides: Local farmers have stated that botanical extracts from plants grown nearby are advantageous (Prasanna et al., 2018). Botanical pesticides are a better substitute for synthetic insecticides, which may be more harmful to the environment, slow down recovery, and raise consumer costs (Shah et al., 2020). These chemicals are also to blame for the rise in insect resistance (Gul et al., 2019). A few botanical extracts include *Jatropha curcas*, *Nicotina tabacum*, *Milletia ferruginea*, *Chrysanthemum cinerariifollium*, *Croton macrostachyus*, *Phytolacea docendra*, which might be used as insect pest management (Rizqullah et al., 2023). About fifty botanical pesticides have been approved for the management of FAW in more than thirty countries; of these, twenty-three are recommended for field experiments and bioassays (Bateman et al., 2018). Under laboratory circumstances, botanical pesticides caused 80% of the deaths (Zaman et al., 2024). Neem extracts have demonstrated a 70% death rate in FAW (Silva et al., 2020). It was discovered that *Eucalyptus urograndis* was more beneficial in protecting maize from pests (Hruska, 2019). It was discovered that Carica's papaya seed powder worked well as a chemical pesticide (Sagar et al., 2020). When neem oil is applied at a concentration of 0.17–0.33%, maize is less affected by FAW (Babendreier et al., 2020). In contrast to chemical pesticides, botanical insecticides are ineffective for natural enemies, do not harm the environment, and are unique to a single target (Mora et al., 2018) (Table 3).

Table 3. Plant based pesticides to combat FAW

Extract uses	Action mode	Species	References
0.25 percent neem oil	Larvicidal with a laboratory death rate of up to 80%	Indian lilac	Zaman et al. (2024)
Wood-based dichloromethane extracts	Larvicidal and insect growth-regulating (IGR) with up to 95% mortality	Spanish-cedar	Paredes et al. (2021)
Extracts of roots and other aerial components in methanol	Controlling insect growth (IGR), larvicidal, and postponing pupation	Bilberry cactus	Paredes et al. (2021)
Ricinine and castor oil (seed extracts)	Suppression of growth and larvicidal	Castor Oil Bean	Kombieni et al. (2023)
Leaf ethanolic extracts	Synergistic with insecticide; antifeedant to larvae	Belly-ache Bush	Mendesil et al. (2023)

10. Conclusion and prospects

Spodoptera frugiperda, a harmful insect, necessitates the creation of FAW-tolerant/FAW-resistant germplasm in Africa and Asia. Conventional breeding faces challenges due to low resistant genotype frequency. Expanding the search for native genetic resistance and implementing genomic regions is crucial. There is a greater chance that this insect will spread globally, drastically reducing agricultural productivity and output. "Fall armyworm" control calls for an integrated management approach, wherein inspections in the field during the early stages of a pest assault and the discovery of the regulating mechanism are essential components. The high fertility rates and rapid spread of the pest made isolated management attempts ineffective in achieving the desired level of pest control. Frequent monitoring and scouting are required to identify pests and evaluate treatment choices. To address invasive pest species like FAW (*S. furgiperda*), it is advised to contact the Invasive Pest Study Center (IPSC) as well as Tuta absoluta Meyrick, the tomato leaf miner. The overall prevalence of the pest can be decreased by implementing an awareness program through advisory services that explains how to identify the pest, what damages it causes, and how to take effective control measures. By putting in place a campaign to raise awareness through advisory services that explain how to identify the pest, what damages it causes, and how to conduct effective control measures, the overall incidence of the pest can be decreased. The actions can promote international stability by reducing the frequency and damage caused by insect outbreaks. It can be recommended to take a collaborative approach, which is essential for controlling the fall armyworm.

Author Contributions

MAF, MI and ANA: Writing original draft and Figure preparations. **SB, EF, TK, HA and TS:** Conceptualization, Collecting literature, Software, Validation, Visualization, Writing– review & editing. **AA:** Conceptualization, writing– review & editing. **MT** and **ABA:** Finalization, Writing– review & editing.

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