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Review Article

Microbial Control Agents Against Fall Armyworm (*Spodoptera frugiperda*): Current Challenges and Future Prospects

Abdifitah Ali Abdirahman[1], Hassan Ahmed Mohamed[2]*

[1]Department of Plant Protection, Faculty of Agriculture, Isparta University of Applied Sciences, Isparta, Türkiye
[2]Trial Officer, Department of Research and Extension, Ministry of Agriculture and Irrigation, Federal Republic of Somalia

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Abstract: The fall armyworm (FAW), *Spodoptera frugiperda*, is a polyphagous pest native to the American continent that was first detected in Africa in 2016, where it has since become a major constraint to agricultural crops. The fall armyworm, *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae), poses a significant threat to maize production, capable of inflicting total yield loss. This lepidopteran pest's polyphagous nature and ability to infest crops from the seedling through the reproductive (cob formation) stages make its outbreaks particularly devastating. FAW has two genetic strains: the "rice strain" that prefers rice and other grasses, and the "maize strain" that feeds on maize and sorghum. Potential control strategies are often more suitable for farmers who lack the financial resources to purchase chemical pesticides or expensive pure seeds. *Spodoptera frugiperda* is extremely difficult to manage because of its capacity for fast reproduction, migration, and feeding on a variety of host plants. However, there are a number of pest management strategies that have been documented in other regions of the world that may be modified, verified, and applied in in many parts of East African countries. The excess application of chemical insecticides has negative impact on the ecosystem and human health, as well as the development of insect pest resistance, this had led to a search for cost-effective, low-risk, and target-specific alternatives. This review focuses on the efficacy of microbial pest management options, including entomopathogenic fungi, entomopathogenic nematodes, bacteria, and baculoviruses. Recommendations highlighted in this paper would undoubtedly pave the way for successful management of fall armyworm in maize and other related crops.

Keywords: *Spodoptera frugiperda*, Microbial biological control agents, eco-friendly, nanotechnology, maize.

1. INTRODUCTION

The Fall armyworm (FAW), *Spodoptera frugiperda*, is the world's most important pest, causing significant maize crop losses. FAW was initially described in 1797 as a consuming pest native to the subtropical and tropical areas of America. It is a member of the Noctuidae family in the Lepidoptera order [1]. FAW is a devastating pest that affects approximately 186 plant species in 42 families. Poaceae, Fabaceae, Solanaceae, Asteraceae, Rosaceae, Chenopodiaceous Brassicaceae, and Cyperaceae are primarily impacted. The FAW feeds plant stems, leaves, reproductive organs, and nearly every stage of the crop.

Spodoptera frugiperda, commonly known as the Fall Armyworm (FAW), was first identified on the African continent in 2016 [2]. By the end of 2017, its presence had been confirmed in over 30 countries across tropical and southern Africa, including Cabo Verde, Madagascar, and the Seychelles, establishing it as one of the continent's most prolific invasive pests. The Food and Agriculture Organization's global warning system classifies it as a major cross-border migratory pest [3], a designation that reflects its rapid transcontinental dispersal within a short timeframe. Since its first identification in the region in 2016, FAW has caused significant agricultural losses in East Africa, notably maize (*Zea mays*), a crucial staple crop. In Ethiopia, Somalia, and Kenya, FAW infestations have led in maize yield losses ranging from 20% to over 50%, with some smallholder farmers facing near-total crop failure [4,5].

In Kenya, annual maize losses due to FAW are anticipated to reach $200-$480 million, aggravating food

***Corresponding Author:** Hassan Ahmed Mohamed
Trial Officer, Department of Research and Extension, Ministry of Agriculture and Irrigation, Federal Republic of Somali

insecurity and economic distress [6]. Ethiopia has had infestations on over 800,000 hectares of maize, greatly raising production costs for pest control. Somalia, already dealing with climatic shocks has inadequate capability to handle FAW, resulting in increased food shortages [7]

The FAW is a destructive insect; if no preventative techniques are undertaken, CABI (2017) forecasts that the bug would cost African countries 6.1 billion US dollars in income loss. FAW travels around 500 km before beginning to lay eggs [8]. A single generation of FAW moths can spread over 500 kilometers from their emergence location due to wind [9]. Despite its extensive host range, FAW is the most serious danger to maize in sub-Saharan Africa. This crop offers critical nutrients and promotes animal feed production throughout the region [10]. Its sustainability is essential for food security since more than 300 million people are fed by the more than 27 million hectares that are farmed. However, FAW infestations have increased agricultural instability, especially for vulnerable communities, by causing large output losses. As a result, a lot of farmers use synthetic pesticides, which raise production costs and lower farm revenue. Access to wholesome food is restricted as a result of rising food prices brought on by the output drop. Furthermore, FAW outbreaks cause supply chain disruptions in agriculture, resulting in market uncertainty for farmers and consumers in impacted areas.

In Africa, cultural control strategies have been demonstrated to be successful [11]. however chemical-based insecticides are the most often used strategy. However, excessive use of conventional insecticides and dependence on them as a single control approach may promote the establishment of resistant FAW populations, making the long-term solution inefficient and unsustainable [11]. Multiple applications or large doses of insecticides have been shown to kill numerous beneficial insects, including natural enemies of FAW, damage the environment, and endanger farmers and consumers' health Thus, there is an urgent need to discover and implement biological options for long-term management of FAW in newly invaded regions. Microbial-based insecticides have long been used in integrated pest control plans.

2. DISTRIBUTION, SPREAD, AND HOST PLANTS

The fall armyworm (FAW), *Spodoptera frugiperda* is, is an invasive pest native to tropical and subtropical America that has expanded substantially across Western Africa and quickly into most Sub-Saharan African countries [12]. It has now spread to over 44 countries on the African continent [12]. The Fall Armyworm (FAW) (*Spodoptera frugiperda*) rapidly spread across East Africa after its first detection in Nigeria in 2016, reaching Kenya, Ethiopia, Somalia, Uganda, Tanzania, Rwanda, and South Sudan by 2017 [13]. Its distribution was facilitated by favorable tropical climates, wind-assisted migration, and widespread maize cultivation [14]. with Kenya and Ethiopia experiencing particularly severe infestations in major maize-growing regions [2]. By 2018, over 70% of maize farms in Kenya reported FAW damage [15]. while Ethiopia documented infestations over 800,000 hectares [16]. In Somalia, FAW worsened food insecurity in southern agro-pastoral zones [17]. and from 2020, nearly all East African countries were affected, with recurring outbreaks linked to climate variability and limited natural predators [18].

In addition to maize, sorghum, rice, sugarcane, cabbage, beet, groundnut, soybean, onion, cotton, pasture grasses, millets, tomato, and potato, fall armyworm can damage more than 350 plant species [19]. Maize is the most popular crop among them [14]. Fall armyworms are sociable pests that may spread locally as well as migrate. Like other Spodoptera moths, it can travel more than 500 km prior to oviposition. When the wind pattern is favorable, moths may fly up to 1600 kilometers [20]. Although it comes periodically in many parts of the planet, it may continue to reproduce year-round and spread to other locations if substitute hosts are available and the weather is favorable.

3. BIOLOGY AND DESCRIPTION OF THE PEST

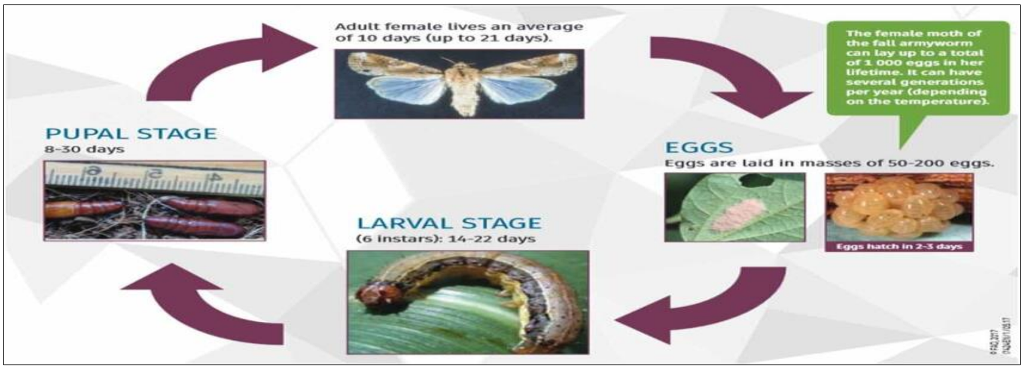

Figure 1: Biology of FAW

The life cycle of *S. frugiperda* comprises of four different phases (Figure 1). Physical traits, distinct signs of damage on susceptible crops, or molecular traits can all be used to identify the Fall armyworm [17]. After passing through four developmental phases, the autumn armyworm (*Spodoptera frugiperda*) completes its life cycle in 30 to 60 days. On host plants, adult moths deposit 100–200 egg masses, which hatch into destructive larvae in two to three days [21] The six instars of the larval stage, which lasts 14–30 days, do significant harm to crops by eating on their leaves, stems, and reproductive organs [22]. After 7–14 days of pupation underground, mature larvae emerge as adult moths, which live for 10–21 days and allow females to deposit many batches of eggs (Montezano *et al.,* 2018). The duration of life cycle may vary depends on temperature, with faster development in warmer conditions [23]. This rapid life cycle enables multiple generations per year, contributing to the pest's explosive population growth and crop damage potential (Figure 1).

The mature larva has a reddish-brown head and brownish coloring. A fully developed larva has been identified by a white inverted "Y" shaped suture. In a cocoon that is typically oval in shape and 20–30 mm in diameter, pupation occurs in the soil at a depth of 2–8 cm. The pupa has an 8–9 day pupal phase and is reddish-brown in color, measuring 14–18 mm in length and 4.5 mm in breadth. The adult's hind wings are silvery-white with a little black mark around the edges, and its color scheme is grey and brown. Being nocturnal, the adult only emerges in the nights during hot, muggy conditions. Adults typically live between seven and 10 days [24].

4. THE ECONOMIC VALUE OF FAW

The larval stage is the most damaging and detrimental stage of the fall armyworm life cycle for crops. Different plant parts, such as leaf whorls, young leaves, cobs, and tassels, depending on the plant's growth stage, can be seen on maize plants infected with FAW larvae [25]. When calculating the loss due to FAW, a number of factors need to be considered. According to some studies crop infestation is often influenced by a number of factors, including the number of pests, the timing of infestation, the pest's natural competitors and diseases at that specific time, and the crop's nutritional and moisture state. The difference in bug occurrence between 26.4% and 55.9% results in an 11.57% decrease in maize output [26]. The yield is reduced by 58% due to 25-50% damage to the leaf, silk, and tassel, while up to 73% of crop production is lost due to 55-100% severity at the mid-late whorl stage [27]. During the reporting period, Ethiopia lost 30.54 million tons of production, Uganda lost 13.91 million tons, and Tanzania lost 3.2 million tons. Fall armyworm affected 250,000 hectares of agricultural land in Kenya, accounting for 11% of the entire area under maize production. Similarly, FAW predicted that Zambia and Ghana lost 40% and 45% of their maize yield, 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 [28].

5. FALL ARMYWORM DAMAGE SYMPTOMS

The fall armyworm's pest stage is the larvae. The young larvae eat the dorsal part of the leaf blade first, leaving the opposite epidermal layer untouched. Insect larvae in their second or third instar burrow holes in young leaves. As the larvae mature, they begin to graze from the border of the leaf inward. In the initial phase of larvae, this affects the leaf in its whorl itself; during complete leaf expansion, the affected plants exhibit characteristic shot hole symptoms [29,30]. 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 [31]. 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 [30]. The crop's leaf damage can be evaluated using the methods (Table 1).

Table 1: Scale for evaluation crop leaf damage caused by armyworm *(S. Frugiperda)*

Scale	Damage
0	No obvious damage to the leaves
1	Leaves with only tiny holes damaged
2	Leaf damage from from pinholes and bullet wounds
3	1-3 Leaves with tiny, elongated lesions (5-10 mm)
4	Lesion of a moderate size (10-30) 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 lesion (>30 mm) are observed.
7	50% of the leaves eaten and elongated lesions (>30 cm).
8	Long (30 cm) lesions and significant wating pieces on 70% of the leaves.

Figure 2: Damage symptoms of FAW

6. MANAGING FALL ARMYWORM WITH MICROBIAL BIOLOGICAL CONTROL AGENTS

Fungi, bacteria, viruses and nematodes are among the many microbial pathogens that are associated with FAW. However, only a small number of these pathogens are in charge of infecting the pests [32].

6.1. Entomopathogenic fungi

Entomopathogenic fungi (EPFs) are recognized as effective bio-agent and represent a key component of Integrated Pest Management (IPM) strategies for controlling the Fall Armyworm (FAW). These fungi possess a broad host range, capable of infecting numerous insect species across various life stages, and can instigate epizootics under favorable environmental conditions.

The infection process begins when fungal spores (conidia) come into contact with the insect's cuticle (integument). The spores germinate and penetrate the host's body wall using a combination of mechanical pressure and enzymatic degradation [34]. Once inside the hemocoel, the fungus proliferates by producing hyphal bodies (yeast-like cells) that circulate in the insect's hemolymph. This extensive growth, combined with the production of mycotoxins, leads to tissue degradation, nutrient depletion, and eventual host mortality. Following death, the fungus emerges from the cadaver to sporulate, producing new infective conidia that can disseminate to other hosts. 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 [35]. 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 [36]. The biocontrol effect of fungi is significantly influenced by moisture content. Among the fungi that may be useful and commonly used when managing FAW include *Metarhizium anisopliae*, *Nomuraea rileyi*, and *Beauveria bassiana* [36]. FAW larvae are more vulnerable to *B. bassiana* than other lepidopteran pests. In vitro studies showed that applying *B. bassiana* to eggs and *M. anisopliae* to second instars caused death rates of 87% and 30%, respectively. In relation to of FAW, laboratory bioassays have shown that *M. anisopliae* is highly pathogenic to both eggs and neonate larvae, with mortality rates of 100% and LT50 values of 2.5 days for the egg stage and 3.1 days for larvae after 48 hours of exposure to maize leaves previously immersed in a suspension of conidia (1 9 108 ml-1) (Lezama-Gutie'rrez *et al.,* 1996).

The rate of mortality of FAW 3rd instar larvae in the laboratory when treated with 5.3 9 105 conidia ml-1 of *M. anisopliae* (strain CP-MA1) was found to be 72.5% 72 hours after infection (Romero Arenas *et al.,* 2014). Similar bioassays recently proved that three *M. anisopliae* strains, Ma22, Ma41, and Mr8, caused 100% mortality in both eggs and neonate larvae (Cruz-Avalos *et al.,* 2019).

Cha'vez *et al.,* (2004) assessed ten *M. rileyi* isolates against FAW larvae at a concentration of 1 9 107 conidia ml-1. Nm-07 was found to be the most effective, causing 100% mortality with lethal times (LT50 and LT90) of 6.2 and 7.9 days, respectively.

6.2. Entomopathogenic Nematodes

Entomopathogenic nematodes (EPNs), particularly those within the families Steinernematidae and Heterorhabditidae, represent an effective biological control agent for various insect pests [37]. Their virulence against the Fall Armyworm (FAW) has been demonstrated in laboratory studies. For instance, isolates of *Heterorhabditis bacteriophora* and *H. indica* were shown to induce 65% mortality in FAW larvae within 48 hours at application rates of 40 and 170 infective juveniles (IJs) per larva, respectively [38]. Studies conducted by Salvadori *et al.,* (2012) identified eight native isolates of entomopathogenic nematodes from southern Brazil with demonstrated potential for controlling *Spodoptera frugiperda* populations in maize. Under laboratory conditions, two isolates from the genus *Heterorhabditis* and one from *Steinernema* induced approximately 70% larval mortality within five days of infection. Comparable mortality rates in *S. frugiperda* were observed when the nematodes were applied to larvae or pupae in the soil. The findings align with previous screenings that reported entomopathogenic nematodes with activity against *Spodoptera* species (Garcia *et al.,* 2008), and with research on the efficacy of Brazilian nematode strains, both alone and in combination with commercial insecticides, for controlling *S. frugiperda* in laboratory and field settings (Negrisoli *et al.,* 2010).

Research by Alonso *et al.,* (2018) further quantified the efficacy of *H. bacteriophora* against later developmental stages. Their findings indicated that a concentration of 5,000 IJs mL^{-1} was the most effective dose, resulting in mortality rates of 92% and 80% for FAW prepupae and pupae under laboratory conditions, and 78% and 62% in greenhouse trials, respectively. Beyond larval and pupal stages, nematodes can also impact adult FAW fitness. Infestation by the ectoparasitic nematode *Noctuidonema guyanense* significantly reduced adult longevity by 30% in males and 15% in females. Furthermore, the fertility of infested female moths was reduced by up to 20% [38]. Bioassays showed that Photorhab dus luminescens SL0708 bacterial isolate, a symbiont of *H. indica* SL0708, is highly pathogenic for FAW larvae. Following a treatment with 1 9 103 1 9 104 CFU larvae-1, 100% mortality was attained after 48h [39,40]. In vegetative field corn, spraying the nematode *S. feltiae* onto maize ears resulted in a significant reduction of FAW larvae but did not positively affect yield. Recently, Fallet et al. (2019) tested EPNs that have been isolated from soil samples in Rwanda and found that they can effectively infect and kill FAW larvae in the laboratory. Since the larvae are targeted in the whorl, the most promising EPNs will be incorporated into a carrier to protect them from desiccation and UV radiation [41].

6.3. Entomopathogenic Bacteria

One of the most common bacterial agents for controlling insects is *Bacillus thuringiensis* (Bt) [42]. These bacteria are Gram-positive, soil-dwelling microorganisms that contribute to the production of naturally insecticidal crystal proteins called delta-endotoxins [43]. There are very few Bt treatments on the market that effectively control lepidopteran pests like FAW. While Bt kurstaki is effective against several lepidopteran pests. FAW is more vulnerable to Bt aizawai and Bt thuringiensis. Current research initiatives are focused on the isolation and characterization of novel *Bacillus thuringiensis* (Bt) strains demonstrating enhanced virulence against *Spodoptera frugiperda*. This effort is critical due to the documented variability in FAW population susceptibility to specific Bt Cry (Crystal) and Cyt (Cytolytic) toxins. In vitro bioassays conducted at the International Centre of Insect Physiology and Ecology (ICIPE) in Africa have identified several promising Bt isolates. Seven highly virulent strains induced 100% mortality in nineteen second-instar FAW larvae within a seven-day observation period. The calculated median lethal time (LT_{50}) values for these strains ranged from 2.33 ± 0.33 to 6.50 ± 0.76 days, indicating a rapid and potent pesticidal effect [44].

In the America, the principal strategy for Fall Armyworm (FAW) suppression relies on the cultivation of transgenic maize. For instance, TC1507 maize, which expresses the Cry1F protein derived from *Bacillus thuringiensis* var. *aizawai*, received regulatory approval in the United States in 2001 specifically for FAW control [45]. The adoption of such transgenic crops across Africa, however, remains limited and subject to significant debate; as of now, South Africa stands as the sole nation on the continent with commercialized Bt maize production. The intensive deployment of these crops has led to the evolution of field resistance in FAW populations to Cry1F maize, a phenomenon documented in Puerto Rico, Brazil, and the United States [46]. To counter resistance development against single-toxin events, the current paradigm in transgenic crop deployment involves the use of pyramided or stacked traits that express multiple Bt proteins with divergent modes of action. Supporting this strategy, a recent investigation evaluated the toxicity of individual proteins—Cry1Ab, Cry1Ac, Cry1Ea, Cry1Ca, Cry2Aa, Cry2Ab, Vip3Aa, and Vip3Ca—and their binary combinations against neonate FAW larvae. The study demonstrated synergistic interactions across all protein mixtures, with the most pronounced toxicity resulting from the combination of Vip3Aa and Cry1Ab [47]. Combinations of Bt toxins should also be given more serious consideration for spray applications in light of the aforementioned favorable results and resistance difficulties generally. This work is now being done at the International Centre of Insect Physiology and Ecology (ICIPE) in Kenya, for example. Several Cry endotoxins (Cry1Ac, Cry1Ab, Cry1Ca, and Cry1Ea) have been used to investigate FAW's susceptibility to *Bacillus thuringiensis*, and variations in susceptibility between them have been noted [48]. A comprehensive survey of *Bacillus thuringiensis* (Bt) strains, isolated from soil samples across 96 counties in ten Brazilian states, was conducted to assess their larvicidal activity against *Spodoptera frugiperda* under laboratory conditions. The evaluation revealed a pronounced variation in virulence, with the majority of isolates (62%) inducing mortality rates between 81% and 100%. In contrast, a significant minority (31%) of the samples exhibited low efficacy, causing less than 20% mortality [49, 50, 51]. Further virulence assays quantified the pathogenicity of specific strains. Suspensions of *Bt* subsp. *aizawai* (strain HD 68) and *Bt* subsp. *thuringiensis* (strain 4412), standardized to a concentration of 3×10^8 cells ml^{-1}, induced mortality rates of 100% and 80.4% in second-instar FAW larvae, respectively. The corresponding median lethal concentration (LC_{50}) values were determined to be 6.7×10^6 and 8.6×10^6 cells ml^{-1} [42]. This high degree of selectivity was corroborated by another study screening one hundred native Brazilian Bt isolates from diverse environmental samples; only eight strains demonstrated high toxicity, defined as exceeding 70% mortality against FAW larvae by the fifth day post-treatment [52]. Beyond direct mortality, several Bt isolates have been documented to induce significant sublethal effects on FAW. These include alterations in key biological parameters, such as reduced larval and pupal weights, which subsequently lead to decreased female fecundity, thereby suppressing population growth [42].

More recently, the virulence of three commercial *Bacillus thuringiensis* strains (KN50, KN11, KNR8; Wuhan Kernel Bio-tech Co. Ltd, China) was evaluated against neonate FAW. The strains exhibited exceptionally high efficacy, with reported LC_{50} values of 0.07, 0.23, and 0.43 µg g^{-1}, respectively. The translational potential of these findings was confirmed in field trials. Application of strain KN50 (32,000 IU mg^{-1}) at rates of 0.3 and 0.6 g m^{-2} resulted in control efficacies of 72.6% and 86.6%, respectively, against mixed-instar larval populations at seven days post-application [53].

6.4. Integrated use of Microbial agents against Fall Armyworm

Both the entomopathogenic nematode *Heterorhabditis bacteriophora* and the entomopathogenic fungus *Metarhizium anisopliae* demonstrate considerable individual efficacy against larval stages of *Spodoptera frugiperda*, establishing their relevance within biological control frameworks. Notably, these biocontrol agents exhibit physiological compatibility when co-formulated in an aqueous suspension, with no detectable antagonistic interactions that reduce the viability or pathogenic function of either organism [61]. This compatibility provides a foundation for combined field application and suggests the potential for synergistic enhancement of insect mortality. Empirical investigations support this potential; studies under controlled laboratory and greenhouse conditions revealed that concurrent application of these entomopathogens resulted in mortality that was either additive or synergistic, significantly surpassing the expected efficacy based on their individual performance [62]. The underlying mechanism for this enhanced effect is hypothesized to involve a multimodal infection process. The nematodes' penetration of the host cuticle may facilitate secondary infection by providing physical entry points for fungal conidia. Concurrently, the fungal infection is thought to attenuate the host's cellular and humoral immune responses, thereby promoting rapid proliferation of the nematodes' symbiotic bacteria (*Photorhabdus spp.*) and accelerating the onset of lethal septicemia.

The practical, high-level efficacy of this combination was conclusively demonstrated under field conditions by Pérez (2016). The application of *H. bacteriophora* at a rate of 0.67 ml m^{-2} alongside *M. anisopliae* at 0.65 g m^{-2} resulted in complete (100%) larval mortality within a five-day post-application period. This result was substantially higher than the mortality achieved by each agent applied singularly, which was 80% for *H. bacteriophora* and 93% for *M. anisopliae* alone. The 100% mortality rate not only outperforms the impact of the most effective single treatment, but it also suggests a synergistic interaction, as the combined outcome exceeds a purely additive effect. These findings suggest a very promising and potentially more cost-effective technique for integrated FAW management, since the combination can provide superior control at lower application rates while harnessing the benefits of two unique biological control mechanisms. The EPN S. carpocapsae and the commercial product Bt Dipel WG (Sumitomo Chemical) were also tested in laboratory bioassays. The results showed promise, with high larval mortality rates of 81.3% after 96 hours, compared to larval mortality caused by *Bacillus thuringiensis* (6.7%) and S. carpocapsae (35%), when applied alone [63]. As the preceding discussion illustrates, the strategic combination of microbial control agents presents a promising avenue for enhancing the management of lepidopteran pests. It is important to recognize, however, that co-infections involving multiple pathogen species can also occur naturally within individual insect hosts. The ecological interplay between these co-infecting agents is complex and can yield contrasting outcomes. Antagonistic interactions may arise from direct competition for host resources and tissues, potentially diminishing the overall pathogenic effect. Conversely, synergistic interactions can occur when infection by one pathogen, such as a virus, increases the host's susceptibility to a secondary agent like a fungus [64]. The specific nature of these interactions—whether antagonistic or synergistic—is highly dependent on factors including the host species, pathogen identity, and the mode and timing of inoculation. Consequently, a critical need exists for further empirical research to elucidate the complex dynamics of microbial interactions within the host environment. A deeper understanding of these mechanisms is essential for rationally designing combined biocontrol strategies that maximize efficacy and ensure predictable, enhanced field performance.

6.5. Combination of microbial agents and insecticide

The combined application of chemical insecticides and EPFs may increase the fungal infectivity of insect pests, according to a number of laboratory and field studies [65]. Prior to a combination trial against *Spodoptera litura*, a study on the compatibility of entomopathogenic nematodes (EPNs) with the pesticide spinosad showed notable differences in concentrations and exposure durations for both *Heterorhabditis indica* and *Steinernema carpocapsae*. All spinosad concentrations were deemed innocuous as they produced less than 20% death, even if longer exposure durations and greater concentrations led to low mortality. Exposure to the highest tested insecticide concentration of 800 ppm induced minimal mortality in entomopathogenic nematodes (EPNs), with rates of only 14% and 13% observed for *Heterorhabditis indica* and *Steinernema carpocapsae* infective juveniles, respectively, after a 48-hour period. This low susceptibility is consistent with prior research. Negrisoli *et al.,* (2008) similarly reported limited lethal effects of Pyrinex™ on *S. carpocapsae* and *Heterorhabditis bacteriophora*, a finding further supported by studies on Dursban™ conducted by Alumai and Grewal (2004) and Gutiérrez *et al.,* (2008) against *Steinernema* species. [66, 67]. A proposed physiological mechanism for this observed resilience suggests that butyrylcholinesterase present within nematode synapses may act as a protective buffer. This enzyme is hypothesized to be preferentially inhibited by organophosphate and carbamate compounds, thereby shielding the essential synaptic acetylcholinesterase from inactivation. Furthermore, the compatibility between EPNs and chemical agents appears to be a strain-specific trait. In laboratory bioassays, De Souza *et al.,* (2012) assessed the influence of the neonicotinoid imidacloprid on key biological parameters of entomopathogenic nematodes (EPNs) from the genera *Steinernema* and *Heterorhabditis*, specifically their viability and infectivity against *Spodoptera frugiperda*. The study found that exposure to the insecticide did not cause significant adverse effects on juvenile survival or their capacity to locate, penetrate, and successfully colonize host larvae. These results indicate a high degree of physiological and behavioral compatibility between the tested EPNs and the chemical agent, supporting their potential for combined use in integrated management strategies [68]. Bioassays conducted by Viteri *et al.,* (2018) provide further evidence for synergistic effects between biological and chemical control agents. Their research demonstrated that combined applications of the entomopathogenic nematode *Steinernema carpocapsae* with reduced-risk insecticides—specifically the anthranilic diamide chlorantraniliprole and the spinosyn spinetoram—yielded significantly greater cumulative mortality in fifth-instar *Spodoptera frugiperda* larvae compared to independent treatments. The most substantial effect was recorded at 72 hours post-application, where combined treatments achieved larval mortality exceeding 90%. This mortality rate substantially surpassed the expected additive effect of each agent applied alone, confirming a truly synergistic interaction rather than simple additive toxicity. To broaden the scope of compatibility, Negrisoli *et al.,* (2010) found that three particular EPN species—*H. indica*, *S. carpocapsae*, and *S. glaseri*—did not significantly lose viability or virulence when exposed to most of the chemical insecticides that are officially registered and approved for use in the Brazilian agricultural sector for the control of FAW larvae in maize cultivation systems. These specific nematode strains appear to be resilient and appropriate for incorporation into chemical-based IPM systems, according to this thorough screening. A later study (Negrisoli *et al.,* 2010) assessed the practical effectiveness of using *H. indica* and *S.* carpocapsae in a tank mixture with the organophosphate insecticide chlorpyrifos and the benzoylurea chitin synthesis inhibitor lufenuron for FAW control in corn, moving from laboratory conditions to a field trial. According to the results of these agronomic field trials, which take into consideration actual factors like soil composition, temperature variations, and precipitation, the combination of EPN *H. indica* and the insect growth regulator lufenuron, applied at a rate of 0.15 liters per hectare, was the most successful treatment protocol. Field validation trials confirmed the efficacy of this specific combination, which yielded consistently high larval mortality rates of 62.5% and 57.5% across two consecutive growing seasons. These results substantiate previous laboratory findings on agent compatibility and demonstrate significant pest suppression under actual field conditions. Complementing these findings, research incorporating entomopathogenic fungi (EPF) indicates that a combined application of *Heterorhabditis bacteriophora* and *Metarhizium anisopliae* with chlorpyrifos can serve as an effective control measure against *Spodoptera frugiperda*, resulting in minimal crop damage [66]. Further supporting the strategic use of combined agents, another study documented a synergistic mortality effect in third-instar FAW larvae following sequential treatment with sublethal doses of spinosad and subsequent applications of *Beauveria bassiana* [69].

7. CURRENT CHALLENGES IN FALL ARMYWORM MANAGEMENT

Effective outbreak management and prediction are greatly hindered by the fall armyworm's life cycle, which includes density-dependent behavioral polyphenism [70]. The erratic outbreaks have a detrimental effect on food security in the impacted nations and cause large food losses [71]. Furthermore, population dynamics are influenced by ecological and human variables, which makes it more difficult to effectively forecast and control epidemics [70]. Unexpected pest outbreaks that are challenging to predict and control are brought on by the changing climate, which is linked to rising global temperatures and extreme weather events including longer and hotter heatwaves, droughts, and heavy, erratic precipitation [72]. Climate change, particularly rising temperatures, tends to benefit certain migratory insects. These heat-adapted pests often see their populations grow, their development cycles shorten, and their migration windows extend. This creates a bigger problem for farmers, who have long relied on chemical insecticides to control them. However, the prolonged use of these chemicals frequently leads to a well-documented issue: field-evolved resistance, which gradually makes the insecticides less effective. Compounding this challenge is the reality for many smallholder farmers. It's common for a single knapsack sprayer to be used for applying both chemical pesticides and biopesticides. This practice can inadvertently lead to cross-contamination. Residual chemicals left in the sprayer can neutralize the living microbial agents in biopesticides, rendering them inactive before they even reach the field. This is a significant hurdle for biopesticides, especially in the fight against *Spodoptera frugiperda* in Africa. Widespread adoption faces major obstacles in both consistent effectiveness and local production. The success of microbial agents like *Bacillus thuringiensis* (Bt), *baculoviruses* (SfMNPV), and fungi such as *Metarhizium rileyi* and *Beauveria bassiana* is highly dependent on environmental conditions. Unfortunately, the high temperatures and low humidity typical of many African farming regions can quickly deactivate these biological treatments. This means they must be applied at just the right time to work, a level of precision that is often impractical for small-scale farmers to achieve consistently.

Furthermore, a critical research gap exists in the identification and characterization of highly virulent native strains adapted to local FAW haplotypes and environmental conditions, which may offer superior performance [73]. Finally, a major impediment to scalability is the lack of cost-effective, stable formulations with adequate UV protection and viable shelf lives that can be maintained without a reliable cold chain, a significant barrier in regions with limited infrastructure Many African countries have lengthy registration procedures for microbial control agents that are based on chemical pesticide models, which hinders local innovation and market growth. At the same time, poor quality control results in inferior goods, which further erodes farmer confidence in biological alternatives, which is already low because they are thought to function more slowly than synthetic pesticides. This problem is made worse by the dearth of extension services that can efficiently impart information on how to employ microbial agents in an Integrated Pest Management (IPM) setting [74].

8. ISSUE FOR FUTURE DIRECTIONS

Fortunately, cutting-edge advances in science and technology are opening doors to powerful new methods for tackling these problems. To truly get ahead of the fall armyworm (*spodoptera furgiperda*) threat, we need to move toward integrated strategies that leverage digital agriculture, genetic engineering, microbial agents and the use of nanotechnology. By integrating these advanced approaches, we can develop control programs that are not only far more effective but also precisely targeted and sustainable for the long term.

8.1. Innovative Digital Technologies

Predictive modeling is an important technique for managing pest outbreaks like armyworms since it predicts environmental suitability and migratory patterns. Species Distribution Models (SDMs) are a good example, since they use data on species occurrences and environmental factors to forecast a pest's geographical spread, allowing them to identify places prone to outbreaks. While various statistical and machine learning models are used, system dynamics models are particularly powerful because they can integrate complex biological, ecological, and human intervention factors to simulate population dynamics [75,76]. Integrating geospatial technology improves the efficacy of these models significantly. The use of satellite remote sensing, GPS, and Geographic Information Systems (GIS) in pest control programs generates useful spatial data, allowing for large-scale, accurate, and dependable monitoring and surveillance. This technological integration is critical for developing early warning systems for migratory pests [77]. Furthermore, the use of artificial intelligence (AI), particularly machine and deep learning, is expected to revolutionize pest management. The integration of AI with other cutting-edge technologies such as the Internet of Things (IoT), robots, and big data analytics is critical. This approach is similar to those used to manage the desert locust (Schistocerca gregaria), where AI-driven early warning systems and machine learning-based SDMs have proven critical to effective management by identifying suitable habitats and informing decision-making to prevent major outbreaks [78].

8.2. Use of Bt Modified crops

Genetically modified Bt maize has proven effective in controlling the African armyworm. In South Africa, two distinct Bt maize events, MON810 (Cry1Ab) and MON89034 (Cry1A.105 + Cry2Ab2), have been planted, and studies have shown that they impair larval survival and growth. The MON89034 event, which expresses two toxins, shows more effectiveness. However, the possibility of field-evolved resistance poses a substantial issue, necessitating proactive resistance management measures such as establishing non-Bt "refuge" zones to limit resistance development [79,80, 81].

Beyond of the recognized Cry proteins, novel transgenic maize events expressing Vegetative Insecticidal Proteins (Vips), such as Vip3Aa20, have considerable potential for controlling armyworms and other Spodoptera species. The research emphasizes the need of assessing the toxicity of these Vip3A proteins on African armyworm populations in various places, as well as investigating the potential for synergistic effects when paired with Cry proteins to improve insecticidal potency and durability. Importantly, Bt maize should be deployed as part of a larger Integrated Pest Management (IPM) plan, not as a stand-alone solution [82,83].

Looking to the future, the CRISPR/Cas9 gene-editing technology provides fresh techniques to population control. This approach might be used to develop gene drives that target genes required for survival or reproduction, diminish pesticide resistance via gene knockout, or alter crucial behaviors like as mating by modifying olfactory receptors. Successful uses in similar Spodoptera species, such as S. litura and S. frugiperda, show the ability to impair development, pheromone response, and odor recognition. As a result, research is proposed to adapt CRISPR/Cas9 for the African armyworm, perhaps combining it with other tactics such as the Sterile Insect Technique (SIT) for improved control [84,85].

8.3. Nanotechnology

Nanotechnology has considerable promise for more effective, sustainable, and ecologically sensitive management of African armyworm outbreaks by providing new solutions across several facets of pest control. Chemical and biological pesticides can be encapsulated in nanoparticles for improved delivery and controlled release [86,87,88], increasing pesticide efficacy while limiting off-target impacts. Furthermore, Nano formulations improve solubility and absorption [88]. and pesticide toxicity through Nano emulsions with improved penetration capacities [89]. Previous research has demonstrated that Nano pesticides have significant potential for suppressing lepidopteran species [90]. For example, using zinc oxide nanoparticles to S. frugiperda caused body deformity and lower fecundity [91]. Another research found 98% and 90% death rates in S. litura larvae treated with silver nitrate and zinc oxide nanoparticles, respectively [92].

Biopesticides, such as plant extracts or microorganisms, are formulated and delivered using a variety of nanomaterials, including nanocapsules, nanogels, nanoparticles, and nanoemulsions, which improve their stability, lifespan, water solubility, and field efficacy [93]. For example, silver nanoparticle formulations of plant extracts have demonstrated significant larvicidal efficacy against S. frugiperda larvae [94]. Beyond delivery methods, nanosensors can detect insect pests or plant stress signals early, allowing for timely interventions to avert large-scale epidemics [88].

Furthermore, nanoparticles, such as zinc oxide, can have direct insecticidal effects by influencing pest formation and life cycles [91]. Furthermore, nanoparticles can be designed to alter insect physiology or behavior via unique pathways [88]. Recent research is progressively combining nanotechnology with RNAi to improve the distribution of dsRNA via nano-enabled delivery systems, consequently contributing to the increased efficiency and stability of RNAi-based insecticides [95]. Concerns have also been expressed about the potential for certain nanoparticles to cause hazardous effects on non-target creatures in the agricultural environment [96]. As a result, more study geared especially to the African armyworm and the African agricultural setting is critical for optimizing and assuring safe use. Importantly, resolving specific restrictions, such as the high cost of nano-based technologies, industrial scalability, ecotoxicity concerns, and other regulatory impediments [97], is critical to the successful development of Nano formulations for pest management.

9. CONCLUSION

FAW, a polyphagous and migratory pest endemic to the Americas, has a significant economic impact on maize, a major crop in many African and Asian nations. FAW can eat on over 300 plant species, allowing it to survive even when maize crop is very scarce. This invasive pest is rapidly expanding and threatening food security in sub-Saharan Africa and Asia due to favorable climate conditions. Given the enormous potential for harm, the ongoing global expansion of FAW, and the known negative consequences of pesticides, it is crucial to create low-risk biologically based management strategies for FAW control. Microbials may be able to contribute significantly to this significant effort, as this review shown. Larger-scale field testing is still necessary for many of these microorganisms to confirm their efficacy in controlling FAW in field situations. This factor should also be considered when assessing the efficacy of biocontrol treatments against FAW in outdoor settings since pathogenic microorganisms may produce sublethal consequences of FAW. The field efficacy of applied microbial agents, such as entomopathogenic nematodes (EPNs) and fungi (EPFs), is compromised by abiotic stressors, including ultraviolet (UV) radiation and elevated temperatures, which diminish their viability and infectivity. To mitigate these detrimental effects, application to maize crops should be confined to early morning or late evening periods. Alternative strategies include the bioprospecting of indigenous microbial strains from hyper-arid environments (e.g., the Atacama Desert) for enhanced stress tolerance or the development of protective formulations, such as micro-encapsulation, to shield microbial inoculants from environmental degradation and improve their field persistence. Better management of insect outbreaks can be accomplished by combining conventional approaches with technology innovations. Furthermore, overcoming the obstacles to the effective use of cutting-edge pest control technologies is essential to maximizing the potential of technology-enabled integrated pest management (IPM) methods against this pest in order to boost agricultural output and food security in Sab-Sahara Africa.

Conflict of Interest

The authors declare no conflict of interest regarding the publication of this manuscript. No financial

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