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REVIEW ARTICLE

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Biological control of *Spodoptera frugiperda* (Nixon) (Lepidoptera: Noctuidae) in new invaded countries using insect pathogens

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Abstract

Background The fall armyworm (FAW), *Spodoptera frugiperda* (J.E. Nixon) (Lepidoptera: Noctuidae), is the major insect pest that infests cereal crops recently in African and Asian countries. The insect is polyphagous that attacks large numbers of host plants, especially maize and rice, causing considerable losses in their annual yield. The integrated pest management (IPM) of the insect depended mainly on insecticides and to some extent on biological control agents including insect pathogens (nematodes, fungi, bacteria and viruses).

Results Different species of entomopathogens (nematodes, fungi, viruses and bacteria) infecting the insect could be isolated in such newly invaded countries. Laboratory and field experiments indicated that the insect was found to be susceptible to the isolated entomopathogens, and thus, they could be promising biocontrol agents against this insect.

Conclusion This review article proved the susceptibility of *S. frugiperda* to the most of tested entomopathogens. However, more field studies have to be carried out in order to include such entomopathogens within integrated pest management programs against this insect pest.

Keyword Fall armyworm, *Spodoptera* frugiperda, Entomopathogens, Entomopathogenic nematodes, Entomopathogenic viruses, Entomopathogenic fungi, *Bacillus* thuringiensis

Background

The fall armyworm (FAW), *Spodoptera frugiperda* (Lepidoptera: Noctuidae), is the major insect pest that recently infests cereal crops in African and Asian countries. The insect is polyphagous that attacks large numbers of plants, especially maize and rice, causing 11.6–32–47% losses in maize yield of the total production/year. Tendeng et al. (2019) reported that the total life cycle of FAW averaged 25 days (22–28 days) at 25 °C. The female can deposit 1500–2000 eggs during its life span which ranges 7–10 days at 28 °C and 60% R.H. (Kumar et al. 2022). On rearing the insect on maize and Okra, the egg duration averaged 2.5 days while the larval duration averaged 13–15 days and the longevity of adults averaged 10.5 and 11.5 days in males and females, respectively (Kumar et al. 2022). *Spodoptera frugiperda* was detected starting from 2016 in West and Central Africa: Rwanda, Senegal, Sudan, Egypt, and over 44 African countries (Abbas 2023). As well, the pest has been recorded in Asia; India, China, Korea, Japan, Vietnam, Philippines, Sri Lanka, Syria, Jordan and Israel since 2016 (Pehlivan and Atakan 2022). The insect successfully invaded Europe (Germany, the Netherlands, Turkey) as well as Australia (Abbas 2023). Tendeng et al. (2019) claimed that FAW has long-distance migration ability that can covers 100 km per night, whereas Goergen et al. (2016) reported that in the Americas, adult moths of FAW could travel

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hundreds of kilometers per night on prevailing winds from their endemic zone to the worm regions. This ability might be one of the factors that facilitates its invasion of different parts of the world.

The IPM of FAW has been carried out worldwide mainly by using chemical insecticides, but because the pest has developed resistance to different groups of insecticides, biological control agents were found to have a great attention. Abbas et al. (2023) recorded 66 parasitoid and predator species of *S. frugiperda* in African countries as well as 35 species in Asian countries since its invasion starting from 2016.

The entomopathogenic nematodes (EPNs) in the two families Steinernematidae and Heterorhabditidae have been recorded as successful biocontrol agents against insect pests worldwide.

The entomopathogenic bacterium, *Bacillus thuringiensis* (*Bt*), is the major biocontrol agent infecting insect pests. It produces one or more crystalline proteinaceous inclusions (Cry toxins) adjacent to the endospore, which have been found to be toxic to invertebrates, mainly insects. *Bt* crops are plants genetically engineered (modified) to contain the toxins (Cry toxins) of *Bt* to be resistant to certain insect pests (Abbas 2018).

The entomopathogenic fungi (EPF) are associated with insects in almost all orders, and are among the most common pathogens that cause diseases in insects naturally. However, very few commercial products of fungi proved to be successful insecticides.

The entomopathogenic viruses include more than 1100 species in 16 families (Adams 1991) and among these, baculoviruses are more promising and have been used as biopesticide with fair success (Inceoglueta1 2006). FAW nucleopolyhedrovirus (SfMNPV), (a baculovirus), has been registered and used commercially in several African and Asian countries for FAW management (Firake et al. 2020; Hussain et al. 2021; Wennmann et al. 2021).

The present article deals with survey as well as laboratory and field evaluation of insect pathogens as biocontrol agents against the FAW in the new invaded countries in Africa, Asia and Australia.

Role of insect pathogens against *S. frugiperda* larvae in African countries (Table 1)

Nematodes (Entomopathogenic Nematodes, EPNs)

In Nigeria, Ottun et al. (2021) found that at the concentration of 250 IJs/5 larvae of FAW, *Heterorhabditis* sp. caused 60% mortality in the treated larvae at 3 days post-treatment. In Egypt, Mohamed and Shairra (2023), evaluated *S. carpocapsae* and *H. indica* against 2nd–6th larval instars and found that *S. carpocapsae* caused 100% mortality in all larval instars at all the tested concentrations (150–2400 IJs). *H. indica* caused 100% mortality in 2nd and 3rd larval instars after 96 h, but 5th and 6th larval

Table 1 Virulence of Entomopathogens against *Spodoptera frugiperda* larvae in African countries

Entomopathogens	Country	Mortality % or LC_{50} (%)	Authors
a. Nematodes			
Heterorhabditis sp.	Nigeria	60	Ottun et al. (2021)
H. indica	Egypt	100	Mohamed and Sheirra (2023)
Steinernema carpocapsae			
S. carpocapsae	Rwanda	72–100	Fallet et al. (2022)
b. Fungi			
Beauveria bassiana	Kenya	30.0	Akutse et al. (2019)
Metarhizium anisopliae 1		96.5	
Metarhizium anisopliae 2		93.7	
Metarhizium anisopliae 3		79.0	
Beauveria sp.	Ethiopia	100	Sisay et al. (2018)
Metarhizium sp.		80	
c. *Bt* and Bt toxins			
Cry1Ab	South Africa	65.9	Botha et al. (2019)
Cry1A + Cry2b2		99.0	
d. Viruses			
Spodoptera littoralis NPV	Kenya	Effective	Bateman et al. (2018)
Commercial baculovirus		45	Mweke et al. (2023)
S. frugiperda NPV	Nigeria	Could be isolated from *S. frugiperda* larvae	Wennmann et al. (2021)

instars required 120–188 h to be killed at all tested concentrations. Also, Sayed et al. (2022) evaluated gamma irradiated and un-irradiated infective juveniles (IJs) of *S. carpocapsae* and *H. bacteriophora* against 3rd and 5th larval instars of *S. frugiperda* (80 IJs/larva). The irradiated *S. carpocapsae* caused 100% mortality in both larval instars, whereas the un-irradiated one caused 72.2 and 77.8% mortality, respectively. The irradiated *H. bacteriophora*,, however, caused 44.4 and 33.3% mortality in 3rd and 5th larval instars, respectively, compared to 44.4 and 22.2% by the un-irradiated nematode.

Bateman et al. (2018), in Kenya, reported that *S. carpocapsae* and *S. feltiae* were registered as biological control agents of FAW in Cameron. Fallet et al. (2022) in Rwanda could isolate *S. carpocapsae* from soil samples. The nematode caused 100% mortality in FAW larvae when formulated in a carboxymethyl cellulose gel at a concentration of 3000 IJs/maize plant in the laboratory. However, it caused 72% mortality when applied in water. Danso et al. (2021), in Ghana, estimated the efficacy of unidentified Steinernematid and Heterorhabditid EPNs compared to the insecticide Emamectin benzoate in a greenhouse planted with maize (in pots). The results showed that both EPNs were as effective as Emamectin benzoate in reducing the numbers of FAW larvae as well as the infestation in maize cobs compared to the control.

The bacterium *Bacillus* thuringiensis (*Bt*) and *Bt* toxins

Botha et al. (2019), in South Africa, evaluated the insecticidal efficiency of *Bt* maize against larvae of FAW fed on leaves of *Bt* maize expressing Cry1Ab (*Bt*1) and Cry1A.105 + Cry2b2 (*Bt*2). The results showed moderate survival (4–35%) on *Bt*1 maize and very high mortality (99%) on *Bt*2. The authors attributed the moderate survival on *Bt*1 to low dose of Cry1Ab in *Bt*1 or to that the insects arrived to the continent might have carried alleles with resistance to the *Bt*1.

Fungi (entomopathogenic *fungi*, EPF)

Akutse et al. (2019), in Kenya, tested 20 isolates of EPF at 1×10^8 conidia/ml for their efficacy against eggs and 2nd instar larvae of FAW as well as the neonate larvae that emerged from the treated eggs. Only *B. bassiana* (ICIPE676) isolate caused mortality of 30% to 2nd instar larvae. *Metarhizium anisopliae* (ICIPE 40) caused 83% mortality in the treated eggs. In addition, *M. anisopliae* (ICIPE 41) and (ICIPE 7) caused 96.5 and 93.7% mortality rates in the neonate larvae. Later, Akutse et al. (2020) tested 22 isolates (16 *M. anisopliae* and 6 *B. bassiana*) against FAW moths. All the 22 isolates were pathogenic to the moths, but the mortality varied significantly among the isolates 7 days post-treatment. *Beauveria bassiana* (ICIPE 621) and *M. anisopliae* (ICIPE 7) were superior among all the other isolates by causing 100% mortality of the moths with the lowest LT_{50} values of 3.6 and 3.9 days, respectively. Sisay (2018), in Ethiopia, found that *Beauveria* sp. and *Metarhizium* sp. were highly effective against FAW larvae inducing 100% and 80% mortality rates, respectively, 5 days post-treatment.

Viruses (entomopathogenic Viruses: Baculoviruses)

Bateman et al. (2018) stated that the commercial product of the cotton leafworm, *Spodoptera littoralis* nucleopolyhedrovirus (SlNPV), which targeted *S. littoralis* was found to be effective against FAW in Cameron and was being registered there. Further, Bateman et al. (2021) reported that commercial isolates of *S. frugiperda* NPV (SfMNPV) have been registered and successfully employed to control the FAW in some African and Asian countries (Kenya, Zambia, Bangladesh and Sri Lanka). In Nigeria, a new *S. frugiperda* multiblenucleopolyhedrovirus (SfMNPV-KA1) could be isolated from larvae of *S. frugiperda* (Wennmann et al. 2021).

Role of insect pathogens against *S. frugiperda* larvae in Asian countries (Table 2)

Nematodes (Entomopathogenic nematodes, EPNs)

In Korea, laboratory studies were conducted by Acharya et al. (2020) to evaluate the efficiency of EPNs against 6th instar larvae and 5-day-old pupae at a concentration of 600 IJs/larva and 600 IJs/10 pupae. In larvae, 100% mortality was achieved by *Heterorhabditis indica* and *Steinernema carpocapsae*, whereas *S. arenarium, S. longicaudum* and *H. bacteriophora* caused 97, 93 and 53% mortality rates, respectively. The emergence rates of adults from treated pupae were 33% (*S. carpocapsae*), 37% (*S. longicaudum*), 40% (*H. indica*), 57% (*S. arenarium*) and 60% (*H. bacteriophora*). Similarly, Lalramliana et al. (2021), in India, treated 3rd and 5th larval instars and 1-day-old pupae of *S. frugiperda* by four EPNs at five concentrations for larvae (10–800 IJs/larva) and four concentrations for pupae (200–1600 IJs/pupa). The tested nematodes were *H. indica, H. baujardi, S. sangi* and *S. surkhetense*. The results revealed that rates of mortality in larvae ranged 43–100% in the 3rd instar larvae, 25–100% in the 5th instar larvae and 37–69% in the pupae.

Wattanachaiyingcharoen et al. (2021), in Thailand, evaluated the efficiency of two indigenous *H. indica* and *S. siamkayai* against FAW larvae in laboratory and greenhouse. In laboratory, 2nd and 5th larval instars were treated at six concentrations (50–300 IJs/larva), whereas in the greenhouse, maize plants in pots, infested with 2nd instar larvae, were sprayed with 100 ml of each of the two species at 20,000 and 50,000 IJs/ml one day after releasing the larvae on the plants. Rates of mortality in 2nd instar

Table 2 Virulence of Entomopathogens against *Spodoptera frugiperda* larvae in Asian countries

Entomopathogens	Country	Mortality % or LC_{50} (%)	Authors
a. Nematodes			
Heterorhabditis sp.	China	84	Wang et al. (2022a)
Steinernema feltiae		100	
H. indica		100	Abbas et al. (2022)
S. carpocapsae		92	Liang et al. (2020)
S. longicaudum		80	
H. indica	Korea	100	Acharya et al. (2020)
H. bacteriophora		53	
S. carpocapsae		100	
S. arenarium		97	
S. longicaudum		93	
H. indica	Thailand	27–82	Wattanachaiyingcharoen et al. (2021)
S. siamkayai		17–67	
H. indica	India	43–100	Lalramliana et al. (2021)
H. baujardi			
S. sangi			
S. surkhetense			
H. indica		100	Patil et al. (2022)
S. carpocapsae			
H. indica strain 1		LC_{50}:21.6 Ijs/larva	Shinde et al. (2022)
H. indica strain 2		LC_{50}:48.9 Ijs/larva	
H. indica	Philippines	100	Duza et al. (2023)
b. Fungi			
Beauveria bassiana	China	54.3	Idrees et al. (2021)
B. bassiana		45.6–53.6	Idrees et al. (2022)
M. anisopliae		57	Idrees et al. (2023)
M. rileyi		56–89% in 1st to 3rd instar	Yan-li et al. (2022)
B. bassiana		> 50	Xu et al. (2020)
B. bassiana		LC_{50}: 7.7×10^5—2.5×10^{11} spores/ml	Gao et al. (2022)
M. anisopliae	India	LC_{50}: 5.8×10^4	Kiruthiga et al. (2022)
M. rileyi		90	Visalakshi et al. (2020)
B. bassiana 1		64	Ramanujam et al. (2020)
B. bassiana 2		57	
M. anisopliae		68	
M. rileyi		50	Firake and Behera (2020)
Metarhizium sp.	Indonesia	70.7–78.7% in 14 isolates	Herlinda et al. (2020)
Nomuraea rileyi		5–79	Ginting et al. (2020)
Endophytic fungi:-			Gustianingtgas et al. (2021)
Beauveria sp. 1		29.3	
Beauveria sp. 2		26.7	
B. bassiana 1	Thailand	91	Rajula et al. (2021)
B. bassiana 2		41.7	
C. *Bacillus thuringiensis*			

Table 2 (continued)

Entomopathogens	Country	Mortality % or LC_{50} (%)	Authors
Bt strain KN 50	China	72.6–86.6% in mixed instars	Li et al. (2019)
Bt corn		95–98	Zhao et al. (2023)
Cry1Ab		LC_{50s} in seven strains of FAW: 087–2.63 ug/g	Wang et al. (2022b)
Vip3Aa		0. 14–0.30 ug/g	
Cry1Ab + Vip3Aa		0.78–1.86 ug/g	
CryAb + Vip3Aa		0.36–1. 42 ug/g	
Cry1Ab		LC_{50s} in different plant areas: 18–538 mg/cm^2 of diet	Xu et al. (2022)
Bt maize (Cry1Ab)		34–100%	Liang et al. (2021)
Bt maize (Cry1Ab)		> 65%	Zhang and Wu (2019)
Bt maize (Cry1Ab + Vip3A)		53–100%	
Vip3A		LC_{5s} in 11 populations: 11. 42–88. 3 ng/cm^2 of diet	Zhou et al. (2023)
Cry1F		111. 2–517 ng/cm^2 of diet	
Cry1Ab		135.8—1108 ng/cm^2 of diet	
Cry2Ab		994—5492 ng/cm^2 of diet	
Cry1Ab		LC_{50s}: 50.3 ng/cm^2 of diet	Li et al. (2019)
Cry1Ac		161. 3 ng/cm^2 of diet	
Cry1F		207. 8 ng/cm^2 of diet	
Cry2Ab		603.7 ng/cm^2 of diet	
Vip3A		Over 800 ng/cm^2 of diet	
D. Viruses			
S.frugiperda NPV (SFMNPV)	India	50	Firake and Behera (2020)
SFMNPV		41–73% in pupae at 5 Conc	Onkarappa et al. (2023)
SFMNPV		LC_{50s} in 3 instars: 4–5 OBs/mm^2	Sivakumar et al. (2020)
SFMNPV		Isolated from FAW larvae	Raghunandan et al. (2019)
SFMNPV		Isolated from 23.7% of 687 collected FAW larvae	Firake et al. (2020)
SFNPV	China	Isolated from FAW larvae	Lei et al. (2020)

larvae at the tested concentrations ranged 27.5–82.5 and 17.5–67.5% by *H. indica* and *S. siamkayai*, respectively. The respective values in the 5th instar larvae were 45 and 32.5% at 300 IJs/larva. In the greenhouse, rates of mortality 10 days post-treatment at 20,000 IJs/pot were 37.9% by *H. indica* and 28.75% by *S. siamkayai.* The respective values at 50.000 IJs/pot were 57.8 and 44.7%.

In China, Abbas et al. (2022) reported that 280 IJs of *Steinernema* sp. could kill 100% of 3rd instar larvae of *S. frugiperda*, whereas 400 IJs of *H. indica* killed only 75%. Also, Wang et al. (2022a) compared the virulence of an indigenous strain of *Heterorhabditis* sp. to a commercial *S. feltiae* against 3rd and 6th larval instars and 5-day-old pupae of FAW in laboratory. The tested concentrations of the nematodes were 100 IJs/larva and 1200 IJs/5 pupae. Rates of mortality in 3rd instar larvae were 84 and 100%, whereas in the 6th instar larvae, they were 56 and 93%, by *Heterorhabditis* sp. and *S. feltiae*, respectively. Rate of adult emergence from treated pupae was 26.7% by both nematodes compared to 93.3% in the control. Chen et al. (2023) evaluated the infectivity of *H. bacteriophora* (HbSD) against *S. frugiperda* under laboratory, greenhouse and field conditions. In laboratory assays, the nematode was highly virulent against the larvae. In greenhouse assays, spraying aqueous formulation of the nematode showed good performance in killing larvae on maize leaves. Patil et al. (2022), in India, reported that *H. indica* and *S. carpocapsae* caused 100% mortality in third- and fourth-larval instars of *S. frugiperda*, and 85% and 72% in pupae, respectively. Treatment of two maize fields, naturally infested with the insect by the nematodes at 2.5×10^8 IJs/ha, showed that *H. indica* significantly reduced the number of larvae and leaf damage. The efficacy of *S. carpocapsae* and *H. indica* applied twice against FAW in sweet corn field was tested by Ratnakala et al. (2023) in India. The results showed that *S. carpocapsae* reduced, significantly, the larval population and leaf damage in the treated crop.

Shinde et al. (2022), in India, evaluated two native strains of *H. indica* (HI-MN and HI-CL) against larval instars of FAW. The LC_{50s} were 21.6 and 48.9 IJs (3rd instar larvae) and 25.5 and 52.4 IJs (4th instar larvae) for HI-MN and HI-CL, respectively. In China, treatment of 2nd instar larvae of *S. frugiperda* with *S. carpocapsae* and

S. longicaudum at 50 IJs/larva caused 92 and 80% mortality, respectively, as reported by Liang et al. (2020). Duza et al. (2023), in Philippines, evaluated the efficacy of three Philippine isolates of *H. indica* (HiBSDS, HiMAP, HiPBCB) and *S. abbasi* (SaMBLB) against two strains of FAW, corn strain (CS) and rice strain (RS). The strain, HiPBCB was the most virulent against the two strains. The highest LC_{50} for SaMBLB, was 36.95 IJs/larva for (CS) and 35.92 IJs/larva for (RS). These values were sufficient to achieve 100% mortality after 48 h for the three *H. indica* isolates.

The entomopathogenic bacterium, *Bacillus thuringiensis* (*Bt*) and *Bt* toxins

In China, Li et al. (2019) reported that *Bt* strain KN50 at a concentration of 32,000 IU/mg caused 72.6–86.6% control in *S. frugiperda* mixed larval instars in a maize field 7 days post-treatment. Wang et al. (2022b) evaluated the susceptibility of seven geographical populations of FAW larvae, collected from three provinces to four *Bt* insecticidal proteins in the laboratory. It was found that the ranges of LC_{50s}were 0.87–2.63 μg/g for Cry1Ab; 0.14–0.30 μg/g for Vip3Aa; 0.78–1.86 μg/g for Cry1Ab + Vip3Aa and 0.36–1.42 μg/g for CryAb + Vip3Aa. Similarly, Zhou et al. (2023) investigated whether the FAW larvae could develop resistance to any of *Bt* corn hybrids planted in China in 11 geographical populations of FAW larvae from corn fields. They found that the ranges of the LC_{50s} of the 4 *Bt* proteins to the 11 populations were 11.42–88.33 ng/cm^2 for Vip3A, 111.21–517.33 for Cry1F, 135.76–1108.47 for Cry1Ab and 994.42–5492.50 for Cry2Ab. The study revealed that all 11 FAW populations proved to be susceptible to Vip3A, Cry1F and Cry1Ab. Xu et al. (2022) reported that the LC_{50} values for FAW collected from different planting areas to Cry1Ab protein ranged from 17.99 to 537.60 ng/cm^2 of diet.

Also in China, Li-Mei et al. (2021), in field experiments, found that the larval density and percentages of damaged leaves and plants were significantly lower in *Bt* plants than in conventional ones. Li et al. (2019) evaluated five *Bt* toxins against neonate larvae of FAW using artificial diet assays. The results showed that the LC_{50} values were 50.3, 161.3, 207.8, 603.7 and over 800 ng/cm^2 of diet for Cry1Ab, Cry1Ac, Cry1F, Cry2Ab and Vip3A, respectively. Zhao et al. (2023), in laboratory bioassays, found that *Bt* corn (DBN3601T) differed significantly in causing mortality in neonate larvae of fall armyworm during 3-year field trials compared to conventional corn. Zhang and Wu (2019) stated that the mortality of FAW larvae fed on leaves of Chinese *Bt*-Cry1Ab maize was less than 65%, whereas the mortality in larvae fed on Chinese *Bt*-(Cry1Ab + Vip3A) leaves ranged 53–100%. Similarly, Liang et al. (2021) reported that the mortality of FAW larvae that fed on different tissues of Chinese *Bt*-Cry1Ab maize DBN9936 ranged from 34 to 100%.

In India, an experiment was conducted to evaluate the efficiency of three products of fungi, a product of a baculovirus, a product of *Bt* and the insecticide, azadirachtin against *S. frugiperda* in a maize field during 2019/2020. Four sprays were applied at 12-day intervals. The results revealed that with fourth spray, *Bt* was the most effective (Wayal et al. 2021).

Endophytic *Bt*

Karshanal and Kalia (2023), in India, reported that *Bt* could be established as endophyte in maize plants using different inoculation methods; seed treatment (ST), soil dranching (SD), foliar application (FA) and combination of all (ST + SD + FA). Feeding FAW larvae on the leaves of such plants caused 50% mortality by ST + SD + FA followed by 40% by ST.

Fungi (Entomopathogenic *fungi*, EPF)

Idrees et al. (2021), in China, evaluated the virulence of *B. bassiana* at three concentrations (1×10^6–1×10^8 conidia ml) against eggs, neonate larvae and 1st–6th larval instars of *S. frugiperda*. At 7 days post-treatment, % mortality in eggs was 40, 70 and 85.6% at the three concentrations, respectively, whereas mortality in neonate larvae was 54.3% at 1×10^8 conidia/ml. However, the 6th instar larvae were not susceptible to infection. Idrees et al. (2022) evaluated 12 isolates of *B. bassiana* from China against eggs and neonate larvae of *S. frugiperda* at a concentration of 1×10^8 conidia/ml. The three isolates, QB.45, QB. 46 and QB.428, caused the highest mortality rates in the eggs; 87.3, 82.7 and 79.3%, respectively, 7 days post-infection. The respective mortality rates for neonate larvae ranged 45.6–53.6% 7 days post-infection and increased to 71.3–93.3% at 14 days post-treatment. Also, and at the same concentration, Idrees et al. (2023) found that *M. anisopliae* caused 86 and 57% mortality in eggs and neonate larvae, respectively. Herlinda et al. (2020), in Indonesia, evaluated the pathogenicity of 14 indigenous isolates of *Metarhizium* spp. against 3rd instar larvae of *S. frugiperda* at 1×10^6 conidia/ml. All isolates were found to be pathogenic to the treated larvae causing 70.67–78.67% mortality. Kiruthiga et al. (2022) studied the pathogenicity of *M. anisopliae* isolated from *S. frugiperda* in Tamil Nadu, India, against 2nd instar larvae of FAW at concentrations of 1×10^3–1×10^8 spores/ml. The mortality reached 18.9–86.7% at 7 days post-infection (LC_{50} value was 5.8×10^4 spores/ml).

Rajula et al. (2021), in Thailand, evaluated six indigenous isolates of *B. bassiana* against larvae of FAW at 1×10^6 and 1×10^8 conidia/ml. All the six isolates caused high mortality 12 days post-treatment with significant differences in their efficacy. The most effective isolate (BCMU6) caused 43 and 91.7% mortality in the treated larvae at 3 and 12 days post-treatment, respectively, at 1×10^8 conidia/ml. The isolate BCMU1, however, caused the least mortality, 3.33 and 41.67%.

Yan-li et al. (2022) could isolate eight fungal strains from diseased larvae of *S. frugiperda* in China. They tested the pathogenicity of *M. rileyi* against eggs, 1st–4th larval instars and pupae at 1×10^7 conidia/ml. Rates of mortality were 88.7, 72.5 and 56.7% in the 1st, 2nd and 3rd larval instars, respectively. Mortality was 56.6% in the eggs and 68.8% in the hatched neonate larvae after 3 days and reached 80.6% after 6 days. However, low mortality was found in the 4th instar larvae (5%) and pupae (14.8%) and did not differ from the control. Xu et al. (2020) compared the virulence of 3 *B. bassiana* strains isolated from soil in China (bbbj, bbzj and bbhn) against 3rd instar larvae of FAW at different concentrations. The strain bbbj had the highest virulence with LC_{50} of 3.37×10^5 spores/ml followed by the strain bbzj (with slightly less effect than bbbj) and then the strain bbhn. The strain bbhn, however, at the highest concentration (1×10^8 spores/ml) caused a mortality less than 50% in the treated 3rd instar larvae in 7 days. Visalakshi et al. (2020) found that spraying 3rd instar larvae of FAW with *M. rileyi* in laboratory at 2×10^8 spores/ml caused 90% mortality in treated larvae within 7 days.

Ramanujam et al. (2020), in India, evaluated 10 indigenous strains of *B. bassiana*, *M. anisopliae* and *M. rileyi,* in India, against larvae of FAW in laboratory. Among the 10 isolates, *M. anisopliae* (strain Ma 35) caused 68% mortality, followed by *B. bassiana* (strain 1) with 64% and *B. bassiana* (strain 2) with 57% mortality. The other seven strains caused 11–29% mortality. In addition, field experiments in maize plots during 2019 showed that *M. anisopliae* (strain Ma 35) caused 70% reduction of infestation and 44% increase in the yield. The respective values for *B. bassiana* (strain 1) were 76% and 55%. Also, Ramanujam et al. (2021) reported that a survey of *S. frugiperda* in maize fields in Karnataka, India, in 2018 revealed that about 20–30% of the collected 4th and 5th larval instars were found to be infected with the fungus, *B. felina*. In China, Gao et al. (2022) stated that the LC_{50s} of *B. bassiana* (strain PfPb) for 1st to the 6th larval instars of *S. frugiperda* were found to be 7.7×10^5, 5.5×10^6, 2.2×10^7, 3.1×10^8, 9.6×10^8 and 2.5×10^{11} spores/ml, respectively, 7 days post-treatment. Firake and Behera (2020) reported that *M. reliye* and *S. frugioerda* NPV (SfMNPV) were observed to be the dominant mortality factors of FAW larvae in corn fields in various locations across Northeast India throughout the season and were responsible for more than 50% mortality of the larvae. Ginting et al. (2020), in Indonesia, reported that *N. rileyi* was found, naturally, infecting 5.3—79% of *S. frugiperda* larvae collected from corn fields in five villages.

In Australia, Apirajkamol et al. (2022) tested six *Beauveria* isolates and five *Metarhizium* isolates against 3rd and 6th larval instars, pupae and moths of FAW. Two *Beauveria* isolates exhibited the highest mortality 7 days post-treatment at 3×10^3 conidia/ml. The isolate B-0571 caused 83, 61, 17 and 94% mortality in 3rd and 6th larval instars, pupae and moths, respectively. The respective values for the isolate B-1311 were 74, 72, 19 and 98%.

Endophytic *fungi*

Sari et al. (2022), in Indonesia, reported that 2-week old seedlings of maize already inoculated with the endophytic fungi, *B. bassiana* and *M. anisopliaea* were used to feed the neonate larvae of *S. frigiperda* for 6 h and were then fed on healthy non-inoculated leaves until pupation. The results showed that the fungal-colonized maize increased the developmental periods of larvae and pupae, significantly. However, % adult emergence, adults' longevity and number of eggs deposited/female were significantly decreased than the control. In addition, Gustianingtyas et al. (2021), in Indonesia, could obtain eight isolates of the endophytic fungi from the corn roots in Indonesia belonging to *Aspergillus* sp., *Beauveria* sp., *Chaetomium* sp. and *Curvularia* sp. and were found to have insecticidal activity against 2nd instar larvae of *S. frugiperda* at 1×10^6 spores/ml. The two most pathogenic isolates belong to *Beauveria* sp. (isolates JgCrJr and JgSPK) with larval mortality of 29.33 and 26.67%, respectively. Also, Herlinda et al.(2022), in Indonesia, stated that out of 20 isolates from endophytic fungi inoculated in corn, four isolates of *B. bassiana,* one isolate of *M. anisopliae* and one isolate of *Curvularia lunata* were found to be more pathogenic to *S. frugiperda* larvae.

Entomopathogenic viruses

Firake and Behera (2020) reported that *Metarhizium reliye* and *S. frugioerda* NPV (SfMNPV) were observed to be the dominant mortality factors of FAW larvae in various locations across Northeast India throughout the season and were responsible for more than 50% mortality of the larvae. Raghunandan et al. (2019) could isolate a nucleopolyhedrovirus from naturally infected larvae of FAW in India. A suspension of 10^8 occlusion bodies (OBs)/ml caused considerable mortality in treated larvae as well as malformation in the formed pupae and adults.

Onkarappa et al. (2023), in India, studied the sublethal effects of the virus SfNPV on the biological parameters of FAW at five concentrations ranged from 3×10^4 to 1.18×10^7 OBs/100ul/late 2nd instar larvae. The results showed that the percentage of pupal mortality ranged from 40 to 72% at varying doses. Longevity of males and females was reduced compared to the control and the egg production of females ranged 150–338/female at the different concentrations compared to 474 in the control. Sivakumar et al. (2020) noticed natural infection of FAW larvae by nucleopolyhedrovirus (NPV) in 2018 in three districts in India. The laboratory bioassay revealed that 1st, 2nd and 3rd larval instars were equally susceptible to infection (LC_{50} 3.71–5.02 OBs/mm^2 of diet).

Firake et al. (2020) could isolate a nucleopolyhedrovirus from collected 687 FAW larvae (in the 2nd and 4th larval instars) from corn fields in India. It was found that 23.7% of the larvae could not reach the adult stage due to infection with SfNPV. Similarly, Lei et al. (2020), in China, could isolate SfMNPV from FAW larvae and analyzed its molecular and biological characteristics. Kenis et al. (2022) reported that *S. frugiperda* NPV (SfMNPV) was registered in Bangladesh, Kenya and Cameroon to be used against FAW.

Combined use of EPNs and the insecticide Spinosad

Kasi et al. (2022), in India, evaluated the combination of the insecticide, Spinosad and each of the nematodes, *S. feltiae* and *H. bacteriophora* against the larvae of FAW in laboratory. The study showed that *S. feltiae* caused 60% mortality at a concentration of 2268 IJs/larva. When combined with Spinosad at a concentration of 400 ppm, the mortality reached 90%. Similarly, *H. bacteriophora* caused 65% mortality alone and 95% when combined with Spinosad. In contrast, Spinosad alone caused 27.5% mortality in the treated larvae.

Conclusion

This review article proved the susceptibility of *S. frugiperda* to the four tested entomopathogens (nematodes, fungi, viruses and bacteria). However, more field studies have to be carried out in order to include such entomopathogens within integrated pest management programs against this insect.

Abbreviations

FAW	Fall armyworm
Bt	Bacillus thuringiensis
SlNPV	Spodoptera littoralis nucleopolyhedrovirus
NPV	Nucleopolyhedrovirus
SfMNPV-KA1	Steinernematid and Heterorhabditid EPNs, multiblenucleopolyhedrovirus

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Competing interests

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