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ORIGINAL RESEARCH ARTICLE

Applicability of entomopathogenic fungi and essential oils against the fall armyworm *Spodoptera frugiperda* (Lepidoptera: Noctuidae)

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Abstract
The fall armyworm, *Spodoptera frugiperda* (Lepidoptera: Noctuidae) is a key polyphagous pest because of the damage it causes to maize crops. The entomopathogenic fungi *Metarhizium anisopliae* AUMC2605 and *Beauveria bassiana* AUMC3563 were evaluated to manage *S. frugiperda* in the lab and field. Additionally, the toxicity of essential oils from *Prunus amygdalus*, *Linum usitatissimum*, *Simmondsia chinensis*, and *Nigella sativa* were detected against larvae *S. frugiperda* in the field. Using the drenches technique, the tested *B. bassiana* AUMC3563 and *M. anisopliae* AUMC2605 isolates were pathogenic to *S. frugiperda* and caused mortality ranging from 10.0 to 80.33%. The laboratory results indicated that *B. bassiana* AUMC3563 was more deadly than *M. anisopliae* AUMC2605. In the fifth instar larval stage *S. frugiperda* was not highly susceptible to the tested fungal isolates. However, the earlier instars larval of *S. frugiperda* were more susceptible to *B. bassiana* AUMC3563 and *M. anisopliae* AUMC2605. *B. bassiana* AUMC3563 caused the highest mortality of first, second, and third instar larvae at 5.6×10^7 conidia ml^{-1} in the laboratory. The field trial results also indicated that the entomopathogenic fungus *B. bassiana* AUMC3563 was more effective than *M. anisopliae* AUMC2605. These results assert the potentiality of entomopathogenic fungi and natural products as effective tools in sustainable and integrated pest management.

Keywords Fall armyworm · Natural products · *Metarhizium anisopliae* · *Beauveria bassiana* · Biocontrol

Introduction

The fall armyworm, *Spodoptera frugiperda* is a serious insect pest that can infect more than one hundred-eighty six plant species belonging to forty-two families of different crops and cause much damage (Montezano et al. 2018). It is a native insect pest to tropical and subtropical crops such as maize, vegetable crops, rice, sorghum, and cotton in the American continent (Nagoshi et al. 2017; Otim et al. 2018; Padhee and Prasanna 2019). Recently, the fall armyworm was reported in West African countries such as Nigeria, Ghana, and Togo on the maize crop (Goergen et al. 2016; Abrahams et al. 2017). The larvae of *S. frugiperda* could cause damage ranging from 10 to 80% in the barley crops and 30 to 90% in the wheat crops (Resendiz et al. 2017; Yang et al. 2020). The *S. frugiperda* larvae were also detected to feed on growing and young organs in the peanut crop causing 65 and 78% loss (He et al. 2020).

Pesticide application is not economical, leading to the evolution of insect resistance, dangerous to farmers, and harmful to natural enemies (Cai et al. 2017; Early et al. 2018). There is a pivotal need to develop alternative techniques to synthetic pesticides; these techniques should be environmentally friendly, safe, and cost-effective to reduce agricultural insect pests. Many pathogens, including viruses, bacteria, fungi, protozoa, and nematodes have been associated with the fall armyworm pest but only a few cause epizootics (Sharanabasappa et al. 2018; Ganiger et al. 2018). Despite *Entomophaga aulicae*, *Erynia radicans*, and *Nomuraea rileyi* fungi can cause high levels of mortality in the insect population, the disease appears too late to alleviate high levels of damage. The hyphomycetous entomopathogenic fungi e.g. *Beauveria bassiana*,

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are common soil dwellers (Ramos et al. 2020). Hence, they can be developed as biocontrol agents against soil-inhabiting pests without risk to non-target insects (Dannon et al. 2020). *M. anisopliae* and *B. bassiana* are aerobic pathogenic fungi that attack insect hosts. They have been extensively studied and widely applied as alternative eco-friendly pest management agents through the biological control of forestry and agricultural crop pests (Balla et al. 2021). These fungi not only infect insects at different life-cycle stages but also exert lasting sustained activity in the next generation (Kaczmarek and Boguś 2021). Host invasion by entomopathogenic fungi occurs via germinating conidia that invade the insect's cuticle and reach the hemolymph (Mannino et al. 2019). Environmental factors, including relative humidity, temperature, nutrient composition, and light, can influence fungal pathogenicity (Mishra et al. 2015). Particularly, both humidity and temperature significantly affects the growth, germination, virulence, and survival of such mycopathogens (Sharma and Sharma 2021). On the other hand, several lines of evidence suggest that natural products contribute to insect pests' management; however, the mechanisms of these insect-natural product interactions need more extensive investigations. There is also a strong tendency in the application of entomopathogenic fungi to gradually drive out chemical fertilizers (Gustianingtyas et al. 2020; Waqas et al. 2021).

Identifying potential natural products and deploying entomopathogenic fungi for insect pest management is one of the fundamental approaches for sustainable agriculture and adopting the next generation. While entomopathogenic fungi are widely suggested for pest biocontrol and sustainable agriculture, natural products e.g. essential oils also seem promising because of their rich content of bioactive compounds and low environmental impact to a greater extent (Fadda et al. 2022; Xu et al. 2019). Natural products of plant origin e.g. essential oils and entomopathogenic fungi such as *Metarhizium anisopliae* and *Beauveria bassiana* are likely candidates as biocontrol agents to manage multiple arthropod pests. The objective of this study was to detect their efficacy on the polyphagous pest *Spodoptera frugiperda* (Lepidoptera: Noctuidae) under laboratory and field conditions.

Materials and methods

Insects and fungi

The eggs of fall armyworm *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae) were obtained from infested maize field in Assiut, Egypt (Fig. 1), and transferred to the laboratory in the Entomology Institute at Asyut, University. Eggs were placed in a Petri dish (15 cm × 0.9 cm) lined with filter paper and examined daily until hatching, the newly hatched larvae were provided with fresh maize leaves. Several pupae were kept in plastic cylindrical cages till adult emergence for a new colony. The newly appeared adults were transferred into adult cages. The ceiling of the cage was supplied with a sterile cotton ball saturated with 10% honey solution. The cotton ball was exchanged daily to guarantee identical egg ages. The fall armyworm colony was maintained in an acclimatized growth chamber at 25 °C, 65% relative humidity, and a photoperiod of

Fig. 1 Shows the damages of fall army-worm larvae to the leaves and ears of maize plant crop

12 h Day Light (Wanjiru and Sunday 2019). Two entomopathogenic isolates *B. bassiana* AUMC3563 and *M. anisopliae* AUMC2605 were obtained from Asyut University Mycology Center (AUMC). The entomopathogenic fungi were refreshed on Difco™ Sabouraud dextrose agar (SDA) and incubated at 25 °C for one week. The newly fungal hyphae were grown on malt extract agar (MEA) for two weeks at 25 °C under static conditions. Conidia were scratched from the surface of the cultures and suspended in a sterile distilled H_2O containing 0.1% Tween 80 (Sigma Chemical Co. Ltd., UK). The spore suspension was mixed properly using a magnetic stirrer for 30 min. The conidial suspension was filtered through clinical gauze to detach the trapped hyphae. The number of spores in the stock conidial suspension was counted using the cell counting chamber (Marienfeld, Neubauer-improved, Germany). A serial dilution (5.0×10^7 to 1.0×10^7 conidia ml^{-1}) was prepared.

Insect fungi-exposure bioassay

The dipping technique was followed during this bioassay; ten larvae of the third instar per replicate were drenched in the conidial suspensions of *B. bassiana* AUMC3563 or *M. anisopliae* AUMC2605. After soaking in the conidial suspension, each treatment was placed in a Petri dish lined with wet sterile filter paper. A solution of 0.1% Tween 80 served as the untreated (control). All Petri dishes were incubated at 25 °C; fresh corn leaf pieces (15 cm) were served daily (Cordero et al. 2014). The larvae were examined daily for fifteen days, and the dead larvae were taken to another sterile moist chamber. The investigations were conducted in triplicate, average values were used, and the LC_{50} was calculated. Under field conditions, an experimental field of 10×10 m^2 cultivated with maize, in the Faculty of Agriculture, Asyut University, was divided and adopted for the field experiment. In this investigation, two concentrations of each entomopathogenic fungus were applied (5.6×10^7 and 9.25×10^7 conidia/ml^{-1}) using a spraying technique. The suspensions were sprayed onto corn seedling leaves (1 ml per leaf) using a Precision Spray Tower (Potter Manufacturing, UK). One week later, the numbers of alive and dead were examined. The mortality value was detected according to the following formula:

$$\text{Mortality (\%)} = \frac{\text{Number of infected (dead)}}{\text{Total number of insects}} \times 100$$

Insect essential oil-exposure bioassay

The test was conducted under field conditions using four different essential oils (Flax oil Jojoba oil, Almond oil, and Nigella). These pure essential oils (100%) were products of The National Research Center in Dokki, Egypt. Under field conditions, a maize plant field (100 m^2) was divided and adopted for this investigation in the experimental agriculture land of Assiut University, Egypt. The population of *S. frugiperda* was recorded from fifty randomly selected plants and sprayed with different concentrations (0%, 1%, 3%, and 5%) for each oil. The oils were sprayed using a 10-L precision tower sprayer (Potter Manufacturing, UK). To calculate the percentages of reduction in larvae of *S. frugiperda*, the numbers of larvae were recorded before and after the oil application according to Henderson and Tilton (1955) formula:

$$\text{Reduction \%} = 1- \left(\frac{\text{n in Co before treatment} \times \text{n in T after treatment}}{\text{n in Co after treatment} \times \text{n in T before treatment}}\right) \times 100$$

where; n = pest population, T = treated, Co = control.

Statistical analysis

The reduction percentages of natural oil and the entomopathogenic fungi in the field were calculated according to Henderson-Tilton's formula (Henderson and Tilton 1955). Data were statistically analyzed using the Statistical Package of the Social Sciences (SPSS) Software Windows (version 20.0). One-way analysis of variance (ANOVA) was done where appropriate. The results were considered statistically significant at $P\leq0.05$.

Results

Mycosis of the fall armyworm larvae

In this study, *B. bassiana* AUMC3563 and *M. anisopliae* AUMC2605 strains were evaluated, as suspension drenches, against the *S. frugiperda* at different larvae stages (Table 1). Treatment efficacies under laboratory conditions were detected by assessing the mortality during development from the 1st instar through to pupae. Both *B. bassiana* AUMC3563 and *M. anisopliae* AUMC2605 were pathogenic to the larvae of *S. frugiperda* but overall mortality ranged between 10.0 and 80.0%, and 0.0% recorded for the treated and control experiments, respectively. In the treated experiment, larvae mortality after exposure to *B. bassiana* AUMC3563 increased from 10.66% to 80.33%. However, mortality by *M. anisopliae* AUMC2605 increased from 10% to 70.66% as the dose was increased from 1.05×10^7conidia ml^{-1} to 5.6×10^7 conidia ml^{-1}. In the laboratory bioassay, the selected isolates evinced high virulence against the first and second instars of the *S. frugiperda* larvae. The isolate *B. bassiana* AUMC3563 realized 80% mortality at concentrations of 1.05×10^7, 2.1×10^7, 4.2×10^7 and 5.6×10^7 conidia ml^{-1} to the first

Table 1 Mortality (%) of the fall armyworm *S. frugiperda* at different larvae stages 624 caused by *B. bassiana* and *M. anisopliae* under Lab. Conditions

Concentration (condia ml-1)	Instar	*B. bassiana*	*M. anisopliae*
5.6×10^7	1st	80.33A±2.1	70.00A±2.1
	2nd	80.00A±3.2	70.66A±2.3
	3rd	80.00A±4.1	70.00A±3.1
	4th	50.66D±2.4	50.00C±1.5
	5th	20.33G±1.2	20.00F±0.9
4.2×10^7	1st	80.00A±3.1	70.66A±1.3
	2nd	80.33A±2.4	70.00A±1.0
	3rd	70.66B±1.9 60	33B±1.2
	4th	40.66E±0.8	40.00D±0.5
	5th	10.00H±0.2	10.66G±0.3
2.1×10^7	1st	80.33A±3.1	60.00B±1.3
	2nd	80.33A±2.4	60.33B±1.4
	3rd	60.00C±2.7	60.00B±1.2
	4th	30.33F±1.3	30.00E±0.6
	5th	10.00H±0.6	10.00G±0.2
1.05×10^7	1st	80.00A±4.2	60.00B±2.3
	2nd	80.33A±3.1	60.33B±1.8
	3rd	50.00D±2.5	50.66C±1.1
	4th	20.66±1.1 20	33F±0.6
	5th	10.66H±0.6	10.00G±0.1
Control	1st	0.00I±0.0	0.00H±0.0
	2nd	0.00I±0.0 0	00H±0.0
	3rd	0.00I±0.0	0.00H±0.0
	4th	0.00I±0.0	0.00H±0.0
	5th	0.00I±0.0	0.00H±0.0

Mean _ SE values within a column not sharing a common letter are significantly different at $P < 0.05$ using Tukey's test

and second instars of the insect (Table 1). Moreover, *B. bassiana* AUMC3563 at a concentration of 5.6×10^7 caused 80% mortality to the third instar. The entomopathogen strain *B. bassiana* AUMC3563 exhibited higher virulence against the fall armyworm than *M. anisopliae* AUMC2605. *B. bassiana* AUMC3563 isolate against *S. frugiperda* larvae caused mortality ranging from 10.0 to 80.33%. However, *M. anisopliae* AUMC2605 caused mortality ranging from 10.0 to 70.66% using the drenches technique. The first instar of *S. frugiperda* larvae showed the highest mortality for the two entomopathogenic fungi. However, the fifth instar of *S. frugiperda* larvae was markedly more resistant to the two entomopathogenic fungi.

Insecticidal indices of *B. bassiana* and *M. anisopliae* in the field

In this study, the virulence of the entomopathogenic fungi strains *B. bassiana* AUMC3563 and *M. anisopliae* AUMC2605 was evaluated in the field. The investigation under field conditions was detected by assessing the mortality during insect development. At a concentration of 9.25×10^7 conidia/ml, *B. bassiana* AUMC3563 and *M. anisopliae* AUMC2605 demonstrated mortality of 81.56% and 71.51%, respectively. The results seem to be less effective than those under laboratory conditions. However, at a concentration of 5.6×10^7, the two applied entomopathogenic fungi achieved 66.23% and 53.57% mortality, respectively (Table 2). Either under the field or laboratory conditions *B. bassiana* AUMC3563 strain seems to be more virulent than the *M. anisopliae* AUMC2605 strain.

Table 2 Mortality caused by the entomopathogenic fungi on the fall armyworm *S. frugiperda* under field conditions

Isolates	Concentration (condia ml^{-1})	Mortality (%)
Beauveria bassiana	9.25×10^7A±8.6	81.56A±2.3
	5.6×10^7B±11.3	66.23C±1.7
Metarhizium anisopliae	9.25×10^7A±15.2	71.51B±2.2
	5.6×10^7B±10.3	53.57D±1.3
Control	0C±0	7.7E±0.8

Mean _ SE values within a column with different letters are significantly different a $P < 0.05$ using du s test

Insecticidal properties of essential oil

The four essential oils exhibited significant insecticidal properties against the fall armyworm larvae. The essential oils at concentrations of 3% and 5% were very effective against *S. frugiperda* larvae (Table 3). The highest insecticidal activity was noticed at 3% v/v of the Jojoba oil (100% mortality), and the lowest insecticidal effect was detected at 1% v/v *Nigella sativa* oil (0% mortality). The insecticidal effect of the *Nigella sativa* oil achieved 100% mortality only after 48 h at 5% (v/v) of the oil. However, the same concentration showed 88.88% mortality after 24 h of application. Bitter almond oil at 5% (v/v) caused 87.5% mortality to the larvae of *S. frugiperda*, 80% mortality at 3% (v/v), and only 22.22% mortality at 1% (v/v). However, Nigella oil at 1% (v/v) didn't show any mortality. Jojoba oil at 3% (v/v) showed complete inhibition (100% mortality) to the *S. frugiperda* larvae in the field after 24 h, and only 63.63% mortality at 1% (v/v) on the second day. Jojoba oil at 3% (v/v) revealed 100% mortality against *S. frugiperda* larvae on the first day. Flax oil at a very low concentration (1% (v/v)) could inhibit the *S. frugiperda* larvae in the corn field by mortality of 90%. Jojoba oil at 3% (v/v) revealed 100% mortality against *S. frugiperda* larvae on the first day and only 63.63% mortality at 1% (v/v) on the second day. The flax oil at 3% (v/v) revealed complete death (100% mortality) on the second day. The flax

Table 3 Natural oil influence on the larvae of fall armyworm *Spodoptera frugiperda* in a corn field at Assiut, Egypt

Natural product	Conc. %	Mortality 1st d	Mortality 2nd d
Bitter almond oil	1	22.22E±0.4	22.22E±0.3
	3	80.0C±2.6	80.0C±1.3
	5	87.5B±1.8	87.5B±1.6
Flax oil	1	88.88B±3.1	90.9B±2.1
	3	90.9B±3.6	100A±3.1
	5	100A±3.2	100A±3.2
Jojoba oil	1	54.54D±1.6	63.63D±1.6
	3	100A±2.1	100A±3.1
	5	100A±2.2	100A±2.7
Nigella sativa oil	1	0G±0	0G±0.1
	3	77.77C±1.8	85.71B±1.6
	5	88.88B±1.9	100A±3.2
Control		10F±0.3	10F±0.6

Mean _ SE values within a column not sharing a common letter are significantly different at $P < 0.05$ using Tukey's test

oil showed a relatively high insecticidal effect (88.88% mortality) at 1% (v/v) of the oil (Fig. 2). Both Jojoba and flax oils showed highest insecticidal effect against the fall armyworms larvae (100% mortality) on the first day at 3% (v/v) and 5% (v/v) of the oil, respectively. However, 3% (v/v) of Flax oil showed 100% mortality in the next day. After one day of application, the flax oil showed 88.88%, 90.9%, and 100% mortality at 1% (v/v), 3% (v/v), and 5% (v/v), respectively. However, the lowest insecticidal effect was exhibited by Nigella oil at 1% (v/v) (0% mortality) even after the second day of treatment.

Discussion

The fall armyworm *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae), is one of the most aggressive pests worldwide, and causes considerable losses in host crops. The fall armyworm comprises two strains, the rice strain, which feeds upon rice and other grass plants, and the maize strain, which refers to maize and sorghum (Abbas et al. 2022; Kumar et al. 2022). The public awareness for healthful environment increased the attention on microbial bio-control agents (Paddock et al. 2021).

Mortality of the fall armyworm caused by mycopathogens

In the current investigation, the used entomopathogenic isolates showed high virulence against the early instars of the

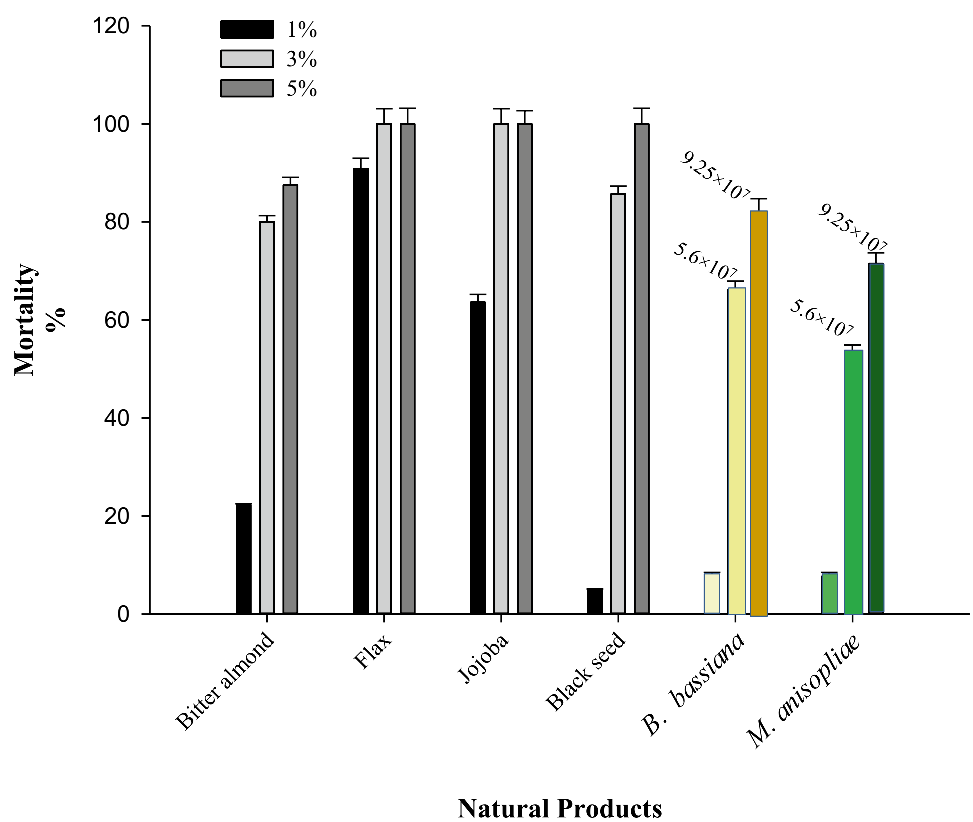

Fig. 2 Shows the mortality (%) of the fall armyworm *S. frugiperda* caused by essential oils at different dilutions and the entomopathogenic fungi *B. bassiana* and *M. anisopliae* at conc. of 5.6×10^7 conidia/ml under the field conditions

fall armyworm larvae. However, the fifth instar of the fall armyworm larvae showed the lowest sensitivity to the two entomopathogenic fungi. Idrees et al. (2021a, b) evaluated the effect of five fungal isolates against immature instars of *S. frugiperda* larvae. There was significant effect on larvae mortality as *B. bassiana* ZK-5 reduced the feeding the activity of the first to the third stage of *S. frugiperda* larvae. Sutanto et al. (2021) reported that the larvae hatched from treated eggs were decreased by the entomopathogenic fungi at 1×10^9 conidia ml^{-1}. The hatchability was significantly reduced by 26.84% in *B. bassiana* and 46.48% in *M. anisopliae*. Conidial concentrations of *M. anisopliae*, *B. bassiana,* and *Isaria fumosorosea* which ranged from 1×10^5 to 1×10^8 conidia ml^{-1} demonstrated virulence on the *S. litura* eggs with mortality of 48.2% to 71.6% (Afandhi et al. 2020). Among the five tested fungal strains, they found that *C. tenuissimum* SE-10, *B. bassiana* ZK5, and *P. citrinum* CTD24 showed significant effects on the insect mortality (Idrees et al. 2021a, b). In this study, conidial concentrations of *B. bassiana* AUMC3563 and *M. anisopliae* AUMC2605 demonstrated virulence on the *S. frugiperda* larvae with mortality ranged from 10.0 to 80.0% under lab conditions.

B. bassiana AUMC3563 strain at conidial concentrations ranged from 1.05×10^7 to 5.6×10^7 conidia ml^{-1} achieved 80% mortality in the early instars of the fall armyworm larvae. Also, using dipping technique the fungal pathogen strain *M. anisopliae* AUMC2605 was effective on the fall armyworm with larvae mortality of 70.66%. Indeed, entomopathogenic fungi are common in maize fields and naturally involved in the suppression of several crop pests (Vega 2018). After the outbreak of the fall armyworm, many larvae infected with mycopathogens were found in maize fields (Chinwada 2018). *B. bassiana* is one of the most common used biological control agents globally (Dannon et al. 2020). Recently, *B. bassiana* demonstrated brilliant pathogenicity against eggs and early instar larvae of the fall armyworm (Gao et al. 2022). Some commercial products, based on *B. bassiana* or *M. anisopliae* are already available and in use West Africa (Rwomushana et al. 2018). Ullah et al. (2022) demonstrated that *M. anisopliae* was more virulent to the fall armyworm larvae than *B. bassiana*. However, *B. bassiana* isolate was more lethal to the *Myzus persicae* nymphs than *M. anisopliae*. At concentration of 1.0×10^9 conidia ml^{-1} *M. anisopliae* caused 88% mortality in *S. frugiperda* and 65% mortality in *M. persicae*. *B. bassiana* exhibited 76% mortality in *S. frugiperda* and 94% mortality in *M. persicae* at the same concentration. Rajula et al. (2021) isolated the entomopathogenic fungus *M. rileyi* during field survey of the fall armyworm *S. frugiperda*. This fungal species has demonstrated 95% mortality of the third larvae instar of the fall armyworm larvae. This finding could be evidence enough to start production of entomopathogenic fungus as a potential bio-pesticide and gain the farmers conviction for application to reduce the insect pest damage (Rajula et al. 2021). Recently, many insecticidal microbial strains have been isolated from soil and effectively used by limited number of farmers as bio-insecticides spray (Kumar et al. 2021). The use of the entomopathogenic fungi *B. bassiana* and *M. anisopliae* in the integrated pest management of the fall armyworm is promising because these fungi can establish endophytic habitat in maize plants (Ramos et al. 2020). Their colonization as endophytes in maize plant caused 100% mortality on the second instar larvae, while 75% and 87% mortality were detected on the forth instar larvae inoculated with *M. anisopliae* and *B. bassiana,* respectively (Ramos et al. 2020). These two entomopathogenic fungi used, caused lethal infection to the different life stages of *S. frugiperda*. In this present data, the fifth instar of *S. frugiperda* larvae showed the lowest susceptibility to the entomopathogenic fungi. The early larval instars particularly the first instar were the most susceptible to *B. bassiana* and *M. anisopliae* (Sutanto et al. 2021). The thick cuticle of pupae may serve as barrier to fungal invasion; therefore, this stage of insect life is seldom being infected by fungal pathogens (Elya and De Fine 2021). Thus, the virulence of a microbial pathogen not only depends on the insect species but also their developmental stage. Bio-control approaches based on *B. bassiana* and *Metarhizium anisopliae* don't just depend upon the interactions between pathogen and host but also on their ambient environmental conditions to which mycopathogens are exposed (Xu et al. 2016).

Botanical insecticidal indices of in the field

Several plant species can produce a wide variety of secondary compounds that possess pesticidal properties and toxic to insect pests (Jaoko et al. 2020). Yarou et al. (2017) listed twenty plants that comprise insecticidal properties to control arthropod pests of vegetable crops. These bio-pesticides are expected to be more environmentally friendly with a more diverse range of bioactive substances compared to synthetic chemical insecticides (Jaoko et al. 2020). Several studies reported that, these botanicals were effective against fall armyworm (Siazemo and Simfukwe 2020; Kardinan and Maris 2021; Rioba and Philip 2020). Botanicals derived from plant extracts in Africa were effective in controlling fall armyworm and also increased the production (Akeme et al. 2021). Sisay et al. 2019 reported seven potential plant extracts that were used in the control of the fall armyworm with mortality higher than 75%. Neem was probably the most effective among the pesticidal plants *Azadirachta indica, Militia ferruginea*, *Jatropha curcas, Schinnus molle*, *Melia abyssinica*, *Eucalyptus globulus*, *Nicotina tabacum*, and *Lantana camara* (Yarou et al. 2017). Moreover, the highest larval mortalities were detected with *Nicotiana tabacum* L. The aqueous extracts of *Cassia nigricans* reduced the fall armyworm infestation in maize by only 13% (Kambou and Millogo 2019). Botanical insecticides based on capsaicin, neem, orange oil, and other aromatic herbs are commercially available in several countries (Bateman et al. 2018). Some botanical pesticides cause high mortality under laboratory conditions. For example, neem extracts demonstrated 70% reduction in the fall armyworm (Matova et al. 2020). *Eucalyptus urograndis* was found to possess properties to protect maize from pests (Andrade et al. 2016). The *Carica papaya* seed powder was detected as an efficient bio-insecticide (Ogbonna et al. 2021). Neem oil at a concentration of 0.17 – 0.33% reduced the fall armyworm damage in maize (Abbas et al. 2022). Botanical insecticides are non-hazardous, target-specific, and environmentally safe for natural enemies (Ahmed et al. 2021). In this investigation, Jojoba oil was probably the most effective among the pesticidal plant oils; the highest larval mortalities were detected at 3% v/v of the Jojoba oil (100% mortality). However, the lowest effective botanical insecticide was *Nigella sativa* oil. The botanical pesticide efficacy is most likely due to the secondary metabolites in the plant such as amides, isobutyl amides, natural lipophilic, and piperine which act as an anti-feedant, deterrent, and neurotoxin (Akeme et al. 2021). Presently, the pesticides market is dominated by the synthetic chemicals despite the development of various botanical pesticides and entomopathogens (Ngegba et al. 2022). An alternative strategy to chemical insecticides still plays a little role in the sustainable agriculture and in integrated pest management. Extracts of neem plant biopesticides are not available on a large commercial scale due to the lack of financial support, materials, and appropriate equipment (Yarou et al. 2017). Our study provides important information of natural products for the field application of biological control of the fall armyworm. Nevertheless, more research is needed to confirm the active property of these natural products as insecticides responsible for protection. Thus, the potential effective botanical insecticides should be communicated and made available for sustainable controlling of the invasive fall armyworm (Deguine et al. (2021). Furthermore, tests must be conducted in greenhouse and field experiments to assess the efficacy of these microbial and botanical pesticides, which can be detected by the reduction in damage and yield increase.

Conclusion

The fall armyworm *S. frugiperda* has become one of the most aggressive pests of maize and other economic crops in Africa and Asia. Among the alternatives to the chemical insecticides, bioinsecticides are an inevitable choice that should be explored. This investigation emphasizes the importance of the entomopathogenic fungi and natural products as biopesticides as biological control agents to reduce the damage of invasive insect pests and increase the productivity of plant crops. The first instar of *S. frugiperda* larvae was markedly more susceptible to the entomopathogenic fungi. Also, the results indicate that *B. bassiana* AUMC3563 strain was more virulent than *M. anisopliae* AUMC2605 strain. Jojoba oil extract achieved the highest reduction of the fall armyworm on maize plant. Thus, natural resources are important source for agro-ecological crop protection using plant biopesticides and biological control agents**.** This data could therefore be used to propose and produce new botanical insecticide that could also reduce the potential threat to the environment.

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Declarations

Competing interests The authors declare that they have no competing interests.

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