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Review Article

Current Advances in the Fall Armyworm (*Spodoptera frugiperda*) Management in Crops: A Comprehensive Review

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Abstract

The fall armyworm [*Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae)] is nowadays considered a major threat to crop production and food security nationwide. *S. frugiperda*, native to the America, has recently been distributed into Africa, Asia, Europe, and Oceania within the last 6 years. Feeding was on 353 host plant species with a high preference for maize crops. Due to the fast spread of *S. frugiperda* worldwide, there is an urgent need to further analyze the control methods of this destructive pest. Therefore, a systematic literature search is conducted for relevant works on this pest. In this review article, the global distribution, host plants, morphology, biology, behavior patterns, strains, economic impact and damage symptoms of *S. frugiperda* are covered. Furthermore, the review focused on *S. frugiperda* management, which includes monitoring, trapping, cultural and chemical controls, biological control (parasitoids, predators, viruses, nematodes, fungi, and bacteria), botanical control (plant extracts), genetically modified crops and host plant resistance. Despite the huge efforts made in the last years to establish IPM strategies, it still so far from controlling the pest in a successful manner. Thus, addressing *S. frugiperda* problem in a coherent manner at a global level is needed to effectively suppress the insect on an eco-friendly sound approach. The most important outcome of this review article is to contribute to the global pool of knowledge regarding *S. frugiperda*.

Keywords: Fall armyworm; *Spodoptera frugiperda*; Invasive pest; Maize; Damage; Control; IPM

Introduction

Invasive pest pressures and pesticide misuse have negative consequences on food safety and security. Insect invasive exotic species represent a difficult challenge in pest control because growers rarely recognize their presence and spread until a huge pest infestation occurs (Toepfer *et al.* 2019). Recently, the fall armyworm [*Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae)] is becoming a major invasive pest causing high yield losses to many crops, especially maize, in much of the world (Deshmukh *et al.* 2021).

S. frugiperda is reported for 200 years in the USA (Edosa and Dinka 2021). In 2016, the pest was firstly reported in some countries of Africa, and hereafter it has been distributed to almost the whole of Africa continent (Allen *et al.* 2021), and in different countries of Asia in 2018 (Hussain *et al.* 2021), and recently, almost all maize producing countries in Asia found under *S. frugiperda* risk (Paredes-Sanchez *et al.* 2021). *S. frugiperda* has recently invaded both Europe and Australia (Plessis *et al.* 2020; Parra *et al.* 2022). The pest has now infested crops in above 109 countries globally (Tepa-Yotto *et al.* 2021; Zhao *et al.* 2022). The insect can damage approximately 353 host plants (Badhai *et al.* 2020; Chen *et al.* 2021a). However, maize is found the most preferred crop by *S. frugiperda* (Chimweta *et al.* 2020). The pest life cycle consists of 4 stages (egg, larva, pupa and adult) (Sagar *et al.* 2020), and it has a very high fecundity (Zhang *et al.* 2021a). The larva is the damaging stage, and it generally feeds on all the developmental stages of the plant (Badhai *et al.* 2020). The insect is an economically important pest due to its voracity (Chen *et al.* 2021a), high reproduction (Zhang *et al.* 2021a), long adult dispersal (Deshmukh *et al.* 2021), multiple generations per year, and absence of diapause (Edosa and Dinka 2021). These characteristics make *S. frugiperda* a risky pest to maize and other crops as well. The economic losses reach 9.4 billion USD in Africa (Eschen *et al.* 2021). Worldwide, the majority of farmers intensively used synthetic insecticides to control insect pests (Al-Zyoud

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2012). Because of the high infestation and fast spreading of *S. frugiperda*, there is an urgent need to understand the control tactics for the pest (Overton *et al.* 2021). Management of the pest appears not easy due to many reasons such as short life cycle, high fertility, a huge number of host plants, voracious feeding habits, fast reproduction, and ability to be distributed across many countries and regions worldwide (Edosa and Dinka 2021; Niassy *et al.* 2021). The management of *S. frugiperda* includes various approaches like monitoring and trapping (Deshmukh *et al.* 2021; Koffi *et al.* 2021), cultural control (Ahissou *et al.* 2021; Niassy *et al.* 2021), chemical control (Bortolotto *et al.* 2022), plant resistant cultivars (Correa *et al.* 2021), botanical control (Paredes-Sanchez *et al.* 2021), and genetically modified crops (Eghrari *et al.* 2022). Furthermore, using biological control to suppress pests is considered a main approach whose efficacy has gone unrealized in several infested cropping systems nationwide (Al-Zyoud *et al.* 2021). Nevertheless, biological control was used to control *S. frugiperda* including parasitoids (Ghosh *et al.* 2022), predators (Souza *et al.* 2021), viruses (Popham *et al.* 2021), nematodes (Huot *et al.* 2019), fungi (Niassy *et al.* 2021), and bacteria (Santos *et al.* 2021).

For the above-mentioned considerations, a systematic literature search for relevant works on *S. frugiperda* was conducted. It is hypothesized that many challenges are faced by farmers to suppress *S. frugiperda* including non-existence of any solid IPM program, failure of early detection of the pest infestation, weak quarantine, and no farmer training on *S. frugiperda* management. Furthermore, it was found that integrating many effective control approaches in an IPM program is the most successful method to control pests in a sustainable manner. Therefore, addressing *S. frugiperda* problem in a coherent manner at a nationwide scale is importantly needed in order to successfully control the pest on sustainable basis. However, there was no integrated study to comprehensively cover the current control tactics, difficulties and future perspectives of *S. frugiperda* eradication despite the damage experienced over the last 6 years worldwide. Thus, this review focused on global distribution, host plants, morphology, biology, seasonal occurrence, behavior patterns, strains, economic impact and damage symptoms of *S. frugiperda*. Furthermore, more attention was paid to the most studied management tactics of *S. frugiperda* including monitoring, trapping, cultural control, chemical control, biological control (parasitoids, predators, viruses, nematodes, fungi, and bacteria), botanical control, genetically modified crops and host plant resistance. The most important outcome of this review article is to contribute to the global pool of knowledge regarding *S. frugiperda*.

A systematic literature search for relevant works on *S. frugiperda* was conducted. The data on *S. frugiperda* were acquired from the Web of Science, Google Scholar, Scopus (Elsevier), and ResearchGate websites. The following search keywords were used: *Spodoptera frugiperda*, fall armyworm, FAW, global distribution, host plants, morphology, biology, life cycle, strains, economic damage, infestation symptoms, management, monitoring, trapping, cultural control, chemical control, biological control, parasitoids, predators, entomopathogens (viruses, nematodes, fungi, and bacteria), plant extracts, genetically modified crops, and host plant resistance. As a positive feature of this comprehensive review article, the majority of references were recent (2017–2022).

Biology and distribution of *S. frugiperda*

Morphology and biology: The life cycle of *S. frugiperda* consists of 4 developmental stages: egg, larva, pupa, and adult (Badhai *et al.* 2020; Sagar *et al.* 2020). The eggs are creamy white, dome-shaped, and have a ventrally flattened base with 0.3 mm in height and 0.4 mm in diameter (Prasanna *et al.* 2018). The eggs are light green in color after one day post-laying, and then they change to golden yellowish, and then to black prior to hatching (Deshmukh *et al.* 2021). The favorable temperature for egg laying is 20–30°C. *S. frugiperda* lays its eggs in clusters on the leaf underside close to the plant base, close to the leaf junction and the stem, or in whorls (Deshmukh *et al.* 2021). Eggs are covered with a grey-pink color layer rubbed off from the abdomen of the females (Bajracharya *et al.* 2019). A female lays in masses of 100–200 eggs (Flanders 2007), and it can lay over 1,500 eggs with a maximum of 2000 during its longevity (Zhang *et al.* 2021a). Most eggs are laid within 4–9 days of female emergence (Flanders 2007), and the egg stage takes 2–3 days during summer (20–30°C) (Badhai *et al.* 2020). The larva has a Y-shaped white stripe on the head, and 4 large squared black dots. Three yellow stripes appear on the upper part of the larvae. The mature larva is 38–51 mm in length (Badhai *et al.* 2020). The larva has 6 instars (Bajracharya *et al.* 2019), and the color changes from one instar to another (Deshmukh *et al.* 2021). The 1st larval instar has green color with a black head, and hereafter it changes to greenish brown throughout the 2nd instar. Starting from 3rd instar onward, the larvae change to brown color with 3 lines on the lateral and dorsal sides (Assefa and Ayalew 2019). The life cycle is shown in Fig. 1. The larva is the damaging stage and generally feeds on all developmental stage of the plant (Badhai *et al.* 2020). The larval stage lasts 14–18 days, depending on temperature and host plant, and most of the feeding is done in the last 4 days of the larval development (Flanders 2007). The larval development takes 11 and 34 days at 32 and 18°C, respectively, and mean development periods of 3.0, 2.1, 2.0, 2.2, 2.3 and 3.4 days were recorded for the 1st to 6th instars, respectively, on sweetcorn kernels at 26°C (Plessis *et al.* 2020). Temperature of 20–30°C is found to be suitable for larval development (Badhai *et al.* 2020), the pest' lowest mortality and fastest development was recorded at a temperature of 30°C (the optimum temperature) (Plessis *et al.* 2020).

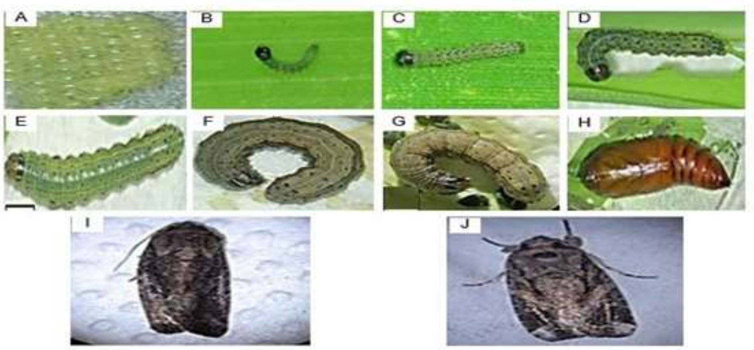

Fig. 1: Life cycle of the fall armyworm, eggs (**A**), 1st larval instar (**B**), 2nd larval instar (**C**), 3rd larval instar (**D**), 4th larval instar (**E**), 5th larval instar (**F**), 6th larval instar (**G**), pupa (**H**), male (**I**), and female (**J**). Modified after Navasero and Navasero (2020)

The full grown larvae go into the soil and combine the soil within 2–8 cm with silk thread to form a cocoon to go into the pupal stage. The pupa is oval-shaped and reddish-brown in color (Day *et al.* 2017), with 4.5 mm in width and 14–18 mm in length (Igyuve *et al.* 2018). The pupal stage takes 20–30 days in winter, and 8–9 days in summer (Badhai *et al.* 2020). If soil is hard for penetrability, the larvae cover themself in leaf debris (Sharanabasappa *et al.* 2018). Forewings are shaded with gray and brown with a triangular bright spot on the apical region of forewings in adult males, while in adult females, the forewings are uniformly greyish brown. Hindwings in both females and males have white in color with narrow dark borders (Badhai *et al.* 2020), and with a wingspan of 3.2 cm (Sharanabasappa *et al.* 2018). The adult longevity is 9–12 days, and the pest completed its life cycle in summer in 30 days on maize, and 60–90 days in winter (Deshmukh *et al.* 2021). The minimum temperature thresholds for egg, larva, pupa, and adult development are 13, 12.1, 13.1 and 12.6°C, respectively (Plessis *et al.* 2020). Degree-day requirements for the development of *S. frugiperda* were 36, 205, 151 and 392 degree-days for egg, larva, pupa, and egg-adult development (Plessis *et al.* 2020).

Strains of *S. frugiperda*: The fall armyworm has 2 strains that differ in their host plant preferences, but they are morphologically similar (Deshmukh *et al.* 2021). The rice strain (R-strain) feeds preferably on millet, rice, and grasses, while the corn strain (C-strain) prefers corn, sorghum, sugar beet, barley, cotton, soybean, sugarcane, tobacco, and wheat (Edosa and Dinka 2021; Zhang *et al.* 2021b). The nuclear triosephosphate isomerase and mitochondrial cytochrome oxidase subunit I (COI) are the most markers used to identify indistinguishable populations of R-strain and C-strain morphologically (Deshmukh *et al.* 2021). The confusion of both strains may be due to the mating of inter-strain (Nagoshi *et al.* 2020). Genetic evidence suggests that *S. frugiperda* from China, Africa, and India indicated that the pest population shares a common origin that derived from a little number of introductions from the Western Hemisphere (Deshmukh *et al.* 2021). Nagoshi *et al.* (2020) indicated 2 evidence lines suggesting that the C-strain predominates in the Eastern Hemisphere. Since, mitochondria is maternally inherited, mating between the females of R-strain and the males of C-strain would produce COI-RS hybrid daughters. If these hybrid daughters mated with C-strain males will produce COI-RS progeny in the C-strain (Nagoshi *et al.* 2020). R-strain is sensitive to plant species, and presents a different behavior to the management tactics, while the C-strain is more tolerant to *Bt.* and synthetic chemicals than R-strain (Salinas-Hernandez *et al.* 2011). Using the whole genome sequencing, Schlum *et al.* (2021) found a panmictic pest population structure, and suggested multiple locations of introduction into the Eastern hemisphere. Both strains have been reported in Africa based on a comparison of specimens from introduced populations with native species in Togo infestations and mitochondrial haplotype similarity in the Caribbean region and the United States (Nagoshi *et al.* 2019).

Global distribution: The fast spread of *S. frugiperda* is mainly due to its high dispersal capacity over long distances and its wide host plant spectrum (Niassy *et al.* 2021). The pest originated in the USA where it has been a serious pest problem for 200 years (Sagar *et al.* 2020; Edosa and Dinka 2021). However, in 2016 the pest was recorded in some African regions and within two years it was distributed to the majority of African countries (Koffi *et al.* 2020a; Allen *et al.* 2021). Similarly, the pest was spread to different parts of Asia in 2018 (Hussain *et al.* 2021), and nowadays, almost all maize producing countries in Asia have been found infested by *S. frugiperda* (Paredes-Sanchez *et al.* 2021). Recently, *S. frugiperda* has invaded Europe (Eschen *et al.* 2021), and Australia (Plessis *et al.* 2020; Parra *et al.* 2022). Based on pest risk prediction, *S. frugiperda* has the potential to spread throughout the whole world (Edosa and Dinka 2021).

Nowadays, *S. frugiperda* is globally distributed in the above 109 countries. Nevertheless, in 2016, *S. frugiperda* is reported in Nigeria, Benin, Niger, Sao Tome, Togo, Guinea, Mali, Senegal, and Sierra Leone (Sisay *et al.* 2019b). In 2017, the pest is recorded in Ghana, South Africa, Malawi, Mozambique, Zambia, Zimbabwe, Congo, Namibia (Harrison *et al.* 2019; Eschen *et al.* 2021), Botswana, Kenya, Rwanda, Tanzania, Uganda, Burkina Faso, Burundi, Cameroon, Ethiopia, Equatorial Guinea, Swaziland (Assefa 2018; Harrison *et al.* 2019), Angola, Central African Republic, Chad, South Sudan (Day *et al.* 2017), and Cameroon (Abang *et al.* 2021). In 2018, the pest was spread in Liberia, Sudan, Yemen, Cabo Verde, Madagascar, Mali, Seychelles, Somalia (Sisay *et al.* 2019b; Tepa-Yotto *et al.* 2021), Mayotte, Reunion, Pakistan, and India (Badhai *et al.* 2020). In 2019, *S. frugiperda* was distributed in Sri Lanka, Bangladesh, Malaysia, Vietnam, Cambodia, Thailand, Nepal, Japan, South Korea, Myanmar, the Republic of Korea, the Philippines, Indonesia, Taiwan, Laos, Egypt and China (Tepa-Yotto *et al.* 2021; Zhou *et al.* 2021; Zhao *et al.* 2022). In 2020, the pest was detected in Australia, Mauritania, Timor Leste, UAE, Jordan, Syria, and New Zealand (Edosa and Dinka 2021; Tepa-Yotto *et al.* 2021), while in 2021 it was found in Spain and New Caledonia (Edosa and Dinka 2021; Tepa-Yotto *et al.* 2021).

Host plants: The fall armyworm is recognized as a destructive global pest, as it is highly polyphagous and can damage approximately 353 host plant species in 76 plant families (Badhai *et al.* 2020; Chen *et al.* 2021a), but maize crop is the most preferred host plant (Chimweta *et al.* 2020). In addition, the pest causes economic damage to sorghum, wheat, potato, rice, bean, soybean, and sugarcane (Montezano *et al.* 2018).

Seasonal occurrence and behavior patterns: Studying insect ecology plays a vital role in understanding insect overwintering mechanisms and its dispersal ability, thus, developing a control approach will suppress its damage to crops (Edosa and Dinka 2021). In addition, understanding the biotic and abiotic factors affecting the pest life cycle is important in forecasting its potential distribution (Ahmed *et al.* 2014). However, high temperature (> 32°C) has been found to negatively affect *S. frugiperda* survival and development, as well as the pest, cannot survive prolonged cold conditions (Nagoshi *et al.* 2012). Thus, it is suggested that *S. frugiperda* migrates during winter to worm and moist regions where host plants are available to overwinter. It was found that environmental conditions affect *S. frugiperda* development, distribution, infestation, mortality, and yearly generation numbers (Sagar *et al.* 2020). The pest preferred humid and warm conditions accomplished by heavy rainfall for its reproduction and survival (Sagar *et al.* 2020), while its development stops below 10°C (Assefa and Ayalew 2019). The presence of host plant availability year-round, and long distance migration of *S. frugiperda* may create a suitable environment for survival and wide dispersal of the pest (Edosa and Dinka 2021). Using wind currents, a *S. frugiperda* generation can spread > 500 km rapidly (Badhai *et al.* 2020), and the pest adults can travel up to 1,600 km under suitable wind currents (Shi-Shuai *et al.* 2021). Assefa and Ayalew (2019) stated 2 generations in temperate areas and 10 generations in tropical and su*Bt.*ropical areas.

High *S. frugiperda* infestation is noticed between November and February since maize plants are still young in this period. According to a related field study, the dry season has been characterized by high pest infestation. (Canico *et al.* 2020). In Ethiopia, two sharp peaks of *S. frugiperda* were observed, in which the 1st peak was noticed in July–August, coinciding with the initiation of the growing phase of the season, and the 2nd peak was observed in February–March, coinciding with the harvesting time (Niassy *et al.* 2021). This pest's cannibalism behavior is critical for larvae survival and the successful colonization of new low-nutrient plants (He *et al.* 2022).

Economic impact and damage symptoms

Economic impact: The pest is an economically important insect due to its voracity (Chen *et al.* 2021a), high reproductive capacity (Zhang *et al.* 2021b), many generations/year, long adult dispersal (Shi-Shuai *et al.* 2021), and absence of diapause (Edosa and Dinka 2021). *S. frugiperda* causes severe damage in developing countries which lack awareness, research work, insufficient resources, expertise, and technical support for pest management. The pest causes damage to many economically cultivated crops, *i.e*., maize, sorghum, rice, and cotton, as well as vegetables, and thus affect negatively the world's food security (Bateman *et al.* 2018). In twelve African countries, *S. frugiperda* has caused yield losses of 9–21 million tons/year of maize, which could feed 41–101 million people annually (Prasanna *et al.* 2018). In Brazil, *S. frugiperda* promotes significant losses of 34–40% in production (Fernandes *et al.* 2019). In 2017, it is estimated that *S. frugiperda* caused an economic loss of three billion USD in Africa (Day *et al.* 2017). Farmers reported average maize losses of 26.6 and 35% in Ghana and Zambia, equivalents of 177 and 159 million USD, respectively (Rwomushana *et al.* 2018). Maize yield loss was 77% in Zambia, 22% in Mozambique, 32% in Ethiopia, 47% in Kenya, and 14% in Zimbabwe (Baudron *et al.* 2019; Kumela *et al.* 2019). It has been predicted that the pest causes losses in maize, sorghum, rice, and sugarcane in sub-Saharan Africa reaching up to USD 13 billion/annum, thus it causes serious problems for livelihoods of millions of farmers (Harrison *et al.* 2019). Kenya loses approximately 1/3 of its annual maize production, equivalent to >1 million tons of maize (Groote *et al.* 2020). In Benin, the pest causes 40% damage to the average annual maize production (Day *et al.* 2017). In the last year, losses of 9.4 billion USD were reported in Africa (Eschen *et al.* 2021). Brazil spends 600 million USD annually on *S. frugiperda* management (Wild 2017). In Nepal, the pest causes a 20–25% reduction in maize yield (Badhai *et al.* 2020). In Kenya and Ethiopia, 0.8–1 ton of maize/ha was lost due to the pest infestation (Kumela *et al.* 2019). Maize farmers lost 797 kg of maize per ha, and this equal about half of the average maize production commonly o*Bt.*ained by them (Houngbo *et al.* 2020).

Damage symptoms: Direct production losses occur *via* larval feeding on developing or mature parts of the plant, *i.e*., ears of maize, cob, or grain, thus directly reducing yields (Harrison *et al.* 2019). Indirect yield damage occurs by defoliation, which reduces grain production due to decrease in photosynthetic area. Qualitative damage of *S. frugiperda* can increase when feeding larvae introduces pathogenic and saprotrophic fungi, leading to grain mycotoxin contamination (Prasanna *et al.* 2018). The larvae feed on a huge amount of green plant tissues, causing glass window-pane like damage on the leaves (Badhai *et al.* 2020). The 1st and 2nd instars could feed on one leaf side, but the bigger larval instars make holes on the leaves (Assefa and Ayalew 2019). Larvae feeding on corn kernels show the fastest developmental rate (Badhai *et al.* 2020). The larva primarily feeds on tender tips, digs into the stem base, and damages maize's young leaf whorls, ears, and tassels, resulting in a lower yield or no harvest at all (Montezano *et al.* 2018). Furthermore, crop growth could be stopped, resulting in no tassel or cob formation. At the advanced damage stage, *S. frugiperda* faecal looks like sawdust in the funnel or on the leaves of maize (Badhai *et al.* 2020). The early instars enter the maize cob through silk, but the bigger instars bore the husk and go inside the cob and feed on the maize kernels (Deshmukh *et al.* 2021). *S. frugiperda* can attack in every developmental stage of the maize crop (Tambo *et al.* 2019). Serious damage is observed when the leaf whorl is destroyed. Pest feeding in young plants may destroy the growing point 'dead heart' in maize, resulting in the cob not being formed (Day *et al.* 2017).

Management of *S. frugiperda*

The major approach to pest management adopted by the majority of growers is the massive of synthetic insecticides (Al-Zyoud 2012; Al-Zyoud *et al.* 2015). Actually, pesticides helped human beings to increase food security by improving crop production via suppression of pests, nevertheless, the intensive use of pesticides in agriculture had many negative effects on humans and the environment. Because of the fast invasion of *S. frugiperda* globally, there is an urgent need to understand management options and tactics of the fall armyworm (Overton *et al.* 2021). The pest's high fertility, voracious feeding habit, migration, and feeding on a wide host spectrum make it very difficult to control (Niassy *et al.* 2021). These can be the most factors that enable *S. frugiperda* to survive all over time and multiply easily. Therefore, if appropriate measures will not be taken, the whole similar areas worldwide will be at high risk of pest invasion (Edosa and Dinka 2021). Management tactics should be utilized in sustainable and cost-effective ways (Naharki *et al.* 2020).

Monitoring and trapping: The fall armyworm monitoring can be done *via* regular field inspection, light and pheromone traps (Gebreziher and Gebreziher 2020; Deshmukh *et al.* 2021). Detecting *S. frugiperda* damage before it causes huge losses is the key to the successful suppression of the pest (Sagar *et al.* 2020), and to implementing IPM strategy (Prasanna *et al.* 2018). Within the first 40 days post planting, it is important to inspect field regularly every 3 to 4 days, and once *S. frugiperda* is detected it is important to take control actions. Within the first 30 days of maize planting, if 5% of seedlings are damaged or 20% of whorls of young plants are infested by *S. frugiperda*, it is recommended to take an efficient management approach to not allow any further pest damage (Assefa and Ayalew 2019). It is suggested that field monitoring should be established twice weekly, beginning with maize seedlings and early whorl stages of the crop (Niassy *et al.* 2021). Furthermore, *S. frugiperda* adults are attracted to light sources (Gebreziher and Gebreziher 2020). Therefore, the use of light traps is considered one of the surveillance mechanisms for this pest. In Ethiopia using night-time light traps indicated good *S. frugiperda* control (Gebreziher 2020). It is important to set up light traps at 2 traps/acre at the time of sowing for monitoring the pest (Badhai *et al.* 2020).

Monitoring using pheromone traps has been found effective in managing *S. frugiperda* adults. The pheromone traps have (Z)–7–dodecenyl acetate (Z)–7–12: Ac), (Z)–9–tetradecenyl acetate (Z)–9–14: Ac), (Z)–9-dodecenyl acetate (Z)–9–12: Ac), and (Z)–11–hexadecenyl acetate (Koffi *et al.* 2021). Therefore, pheromone lures are considered an important option for monitoring and trapping pest (Gebreziher 2020). In Africa, bucket traps are promised, meanwhile, delta traps captured a small number of adults (Deshmukh *et al.* 2021). In Africa, two commercial lures; 3–component or 4–component showed effectiveness in capturing the pest adults on maize (Koffi *et al.* 2021). In Togo it was reported that the 3–component lures (Z9–14:Ac, Z11–16:Ac, and Z7–12:Ac) are more attractive to the pest than the 4–component lure (with Z9–12:Ac) (Meagher *et al.* 2019; Koffi *et al.* 2021). Installation of 2 pheromone traps/ha helps to control *S. frugiperda* (Firake and Behere 2020; Niassy *et al.* 2021). For pest surveillance, bucket traps were installed, and the pheromone traps were hanged post planting, and monitoring started post seedling emergence for adult detection (Niassy *et al.* 2021). The most effective traps for capturing *S. frugiperda* adults were the standard bucket trap (green canopy, and yellow funnel), and the white bucket trap (Hardke *et al.* 2015). According to Cruz *et al.* (2012) use of pheromone traps for monitoring is very important to manage *S. frugiperda* on maize, and 91% larval mortality was recorded when spraying insecticides due to the early pest trapping.

Cultural control: Because of the side effects of synthetic pesticides, there is renewed interest in cultural pest control methods, which have been used for a long time to control pests because they are safe (Al-Zyoud 2012). Cultural methods help in minimizing loss in crops infested by *S. frugiperda* (Sagar *et al.* 2020), and form a main component of IPM for *S. frugiperda* (Gebreziher 2020). The push-pull system is an example of an intercropping system that was found effective in *S. frugiperda* control. It was found that intercropping is less infested by the pest than monocropping, and intercropping has the ability to reduce pest damage by 30% (Houngbo *et al.* 2020). Ahissou *et al.* (2021) demonstrated that intercropping maize with legumes is effective in suppressing the pest. The push-pull tactic involves plants that serve as the "push" component for pests or growing plants at the boarders of main crops to serve as a pull component. In this system, maize is intercropped with silver-leaf or green-leaf desmodium that repel *S. frugiperda*; and Napier, Sudan or Molasses grasses that attract *S. frugiperda* (Midega *et al.* 2018). It is reported that 83% reduction in larvae number/plant and 87% plant damage/plot in areas used push-pull as compared to maize grown in areas as a sole crop with 2.7-fold higher grain yield (Midega *et al.* 2018). The push-pull technology is found to be environment friendly, affordable and effective management approach of *S. frugiperda*, and significantly reduced the pest infestation on maize (Gebreziher 2020; Gebreziher and Gebreziher 2020). Adaption of push-pull gave 2.5–, 2.1– and 3.5–folds higher yields than maize monocrop in Kenya, Tanzania, and Uganda, respectively (Gebreziher 2020).

The cultural control also includes early planting to avoid periods of a high pest population by early harvesting, allowing ears of maize to escape the high *S. frugiperda* infestation that develops later in the growing season (Harrison *et al.* 2019). Prasanna *et al.* (2018) noticed that early planting or growing early maturing cultivars (higher pest density occurs later in the growing season) showed efficiency in suppressing *S. frugiperda*. However, the date of growing has a major effect on pest damage level, due to the synchronization between the insect life cycle and its host plant (Ahissou *et al.* 2021). Other methods include handpicking of larvae, and ash spraying of maize whorls (Badhai *et al.* 2020; Niassy *et al.* 2021). Similarly, clean plant residues and adequate use of fertilizers reduces ear damage by *S. frugiperda* (Sagar *et al.* 2020). Furthermore, stubble burning in invasive areas could kill unhatched all pest stages (Assefa, 2018). Ploughing the soil deeply to expose larvae and pupae to the upper surface of the soil (Assefa 2018), and frequent weeding help in reducing the pest population (Baudron *et al.* 2019).

Chemical control: The use of synthetic insecticides has remained the most widely used method of *S. frugiperda* control in many countries (Sisay *et al.* 2019b; Nboyine *et al.* 2022). Insecticides applied against *S. frugiperda* are effective when used at the right time (Sagar *et al.* 2020). This includes spraying when the larvae are young, spraying in the early morning or later afternoon when the larvae are more active, and directing the spray into the funnel of infested crops (Assefa 2018). Farmers should have enough knowledge of the life cycle of the pest and the best time for spraying synthetic insecticides, *i.e.*, insecticide application will not be effective once the pest larvae are deeply hidden inside the maize whorls and ears, or during the daytime because larvae come out to feed on crops during night dawn or dusk (Day *et al.* 2017).

Several insecticides were recommended for *S. frugiperda* management (Sagar *et al.* 2020). Chlorpyrifos, carbosulfan, and beta cypermethrin have been widely used for controlling pests in Africa (Sagar *et al.* 2020). In India, diamides, avermectins, spinosyns, and benzylureas are recommended for pest control (Sharanabasappa *et al.* 2020). Thiamethoxam with lambda-cephalothin can be applied in severe *S. frugiperda* infestation (Naharki *et al.* 2020). Under laboratory conditions, in a residual contact bioassay against *S. frugiperda*, chlorfenapyr, and clofernapir+zeta-cypermethrin achieved 100% larval mortality (Fernandes *et al.* 2019). Other insecticides commonly used by farmers against the pest include imidacloprid, chlorpyriphos, acetamiprid, permethrin, maltodextrin, cypermethrin, deltamethrin, carbaryl, and fipronil (Chimweta *et al.* 2020; Houngbo *et al.* 2020). In addition, spraying of thiodicarb, spinetoram, acetamiprid, maltodextrin, flubendiamide, chloranthraniliprole, chlorpyriphos, indoxacarb, alpha-cypermethrin and malathion were found effective against *S. frugiperda* (Sharanabasappa *et al.* 2020; Nboyine *et al.* 2021; Niassy *et al.* 2021; Bortolotto *et al.* 2022). According to Sisay *et al.* (2019b) spinetoram and lambda-cyhalothrin caused larval mortality of 100 and 97%, respectively. Under field conditions, Mallapur *et al.* (2019) reported that spinetoram, emamectin benzoate and spinosad showed a reduction of 98, 96 and 96% in the larval population, respectively. The common application intervals used by growers are 7–14 days, and most of them spray four times during the maize cycle (Canico *et al.* 2021). In Ghana the maize was sprayed 12 times during the growing season in 2018 (Tambo *et al.* 2019). Multiple applications of insecticides may lead to fast development of resistance (Deshmukh *et al.* 2021; Paredes-Sanchez *et al.* 2021). The pest has developed resistance against the main groups of insecticides in many countries (Muraro *et al.* 2021). However, due to residues and resistance problems, more environmentally sound control tactics are needed (Lin *et al.* 2021).

Biological control: Biological control is the main approach and it is one of the important alternative tactics of control that provides eco-friendly safe, long-term protection, and is more economically viable than synthetic insecticides (Sengonca *et al.* 2005; Al-Zyoud *et al.* 2007) due to efficient use of natural enemies against several pests (Ghabeish *et al.* 2008; Al-Zyoud *et al.* 2013, 2021). Natural enemies, *i.e.*, parasitoids, predators, viruses, nematodes, fungi, and bacteria play a main role in controlling insect pests (Bhusal and Chapagain 2020). It is obvious recently that there is a need for the application of new control meansthe in agricultural sector (Al-Zyoud *et al.* 2021). However, *S. frugiperda* is attacked by over than 150 parasitoids and predators (Firake and Behere 2020; Koffi *et al.* 2020b), nematodes (Sun *et al.* 2020), viruses, fungi, and bacteria (Shylesha *et al.* 2018; Assefa and Ayalew 2019). Natural enemies cause significant *S. frugiperda* mortality in the USA (Ahissou *et al.* 2021).

Parasitoids

Studies conducted in three African countries indicated the presence of 4 hymenopteran parasitoids; *Charops ater* Szepligeti, *Chelonus curvimaculatus* Cameron, *Cotesia icipe*, Fernandez-Triana and Fiaboe and *Coccygidium luteum* Brullé, and 1 dipteran parasitoid, *Palexorista zonata* Curran (Sisay *et al.* 2019a), in which *C. icipe* is the common parasitoid of larvae in Ethiopia with 34–45% parasitism whereas in Kenya, *P. zonata* is the primary parasitoid with 13% parasitism, and *C. luteum* is the dominant parasitoid in Tanzania with 4–8% parasitism (Sisay *et al.* 2018). In Benin and Ghana, the hymenopterans; *C. luteum*, *C. icipe*, *Telenomus remus* Nixon, *Meteoridea testacea* Granger, *Chelonus bifoveolatus* Szepligeti, *Pristomerus pallidus* Kriechbaumer and *Metopius discolor* Tosquinet, and the dipteran, *Drino quadrizonula* Thomson was found parasitizing 5–38% of *S. frugiperda* (Agboyi *et al.* 2020). *T. remus* attacked the pest eggs in Benin, Kenya, S. Africa, and Niger (Kenis *et al.* 2019), and it is considered the major egg parasitoid of *S. frugiperda* in the USA, where it has been utilized in bio-control programs (Ahissou *et al.* 2021). In fields, *Eiphosoma laphygmae* Costa Lima is the 2nd most player to the pest mortality, after *Chelonus insularis* Cresson, and the parasitoid, *E. laphygmae* is a specialist on *S. frugiperda* in the USA (Allen *et al.* 2021). *E. laphygmae* is considered as a promising bio-control agent against *S. frugiperda* in both Asia and Africa (Allen *et al.* 2021). The egg parasitoids, *Cotesia ruficrus* Haliday, *Glyptapanteles creatonoti* Viereck, and *Campoletis chlorideae* Uchida were reported on *S. frugiperda* larvae in India (Shylesha *et al.* 2018). The larval parasitoid, *Bracon brevicornis* Wesmael parasitizing 84% of the 5th instars of *S. frugiperda*, and in field results showed 54% reduction in infestation after release of *B. brevicornis* (Ghosh *et al.* 2022). According to Birhanu *et al.* (2018), *C. icipe*, *P. zonata* and *C. ater* were emerged from *S. frugiperda* larvae in Ethiopia. *Trichogramma achaeae* Trigac, *T. chilotraeae* Nagaraja and Nagarkatti, *T. pretiosum* Riley, *T. rojasi* Nagaraja and Nagarkatti, *Telonomus remus* Nixon *Archytus incertus* Macquart, *Campoletis flavicincta* Ashmead, *Cotesia marginiventris* Cresson, *C. ruficrus* Hali, *C. curvimaculatus* Cameron, *C. insularis* Cresson, *Euplectrus platypenae* How., *G. creatonoti*, *Lespesia archippivora* Riley, *Microchelonus heliopae* Gupta, and *Archytus marmoratus* Townsend were parasitized the pest (Naharki *et al.* 2020). In Niger, parasitism by *T. remus* was 34% (Amadou *et al.* 2018). In Africa, it is important to involve *T. remus* (Kenis *et al.* 2019), *C. icipe*, *C. ater*, *C. curvimaculatus*, *P. zonata*, and *C. luteum* (Sisay *et al.* 2018, 2019a) to control the pest. In the USA, *C. marginiventris*, *Chelonus texanus* Cresson, *C. insularis* Cresson, *A. marmoratus*, *Ophilon flavidus* Brullé, *Aleiodes laphygmae* Viereck and *Euplectrus platyhypenae* Howard were found attacking the pest (Meagher *et al.* 2016). Ogunfunmilayo *et al.* (2021) reported the parasitoids, *Euplectrus laphygmae* Ferrière and *T. remus*. The efficacy of *T. remus* was demonstrated by Queiroz *et al.* (2019) with nearly 100% parasitism. In Benin and Ghana, 10 parasitoids were recorded on *S. frugiperda*: 2 egg parasitoids (*T. remus* and *Trichogramma* spp.), an egg-larval parasitoid (*C. bifoveolatus*), 5 larval parasitoids (*C. luteum*, *C.*, *Charops sp.*, *P. pallidus*, and *D. quadrizonula*), and 2 larval-pupal parasitoids (*Meteoridea testacea* Granger and *M. discolor* Tosquinet (Agboyi *et al.* 2020). In America and Brazil, the parasitoids, *C. marginiventris*, *C. texanus* and *A. marmoratus* were used to manage the pest (Assefa and Ayalew 2019). In Mexico, more than 88 parasitoids have been recorded on the pest such as *C. marginiventris*, *Meteorus laphygmae* Viereck, *A. marmoratus* and *L. archippivora* (Jaraleno-Teniente *et al.* 2020). *T. remus*, *Trichogramma chilonis* Ishi, *C. luteum*, *C. icipe* and *Cotesia sesamiae* Kitale are parasitoids of *S. frugiperda* in Cameroon, and *C. icipe* showed the highest parasitism rate of 56% (Abang *et al.* 2021). *Cotesia flavipes* Cameron and *C. sesamiae* Cameron caused mortality of 23–36% (larvae) and 10–12% (pupae) as well as 8–38% (larvae) and 4–21% (pupae), respectively in Kenya (Sokame *et al.* 2020). In India, the parasitoids, *Coccygidium transcaspicum* Kokujev (Gupta *et al.* 2020a) and *Chelonus formosanus* Sonan (Gupta *et al.* 2020b) parasitizing eggs and larvae of *S. frugiperda*.

Predators

In the USA, the most reported predators of *S. frugiperda* are the striped earwigs, *Doru lineare* (Eschscholz, *Labidura riparia* Pallas, and *Doru luteips* Scudder (Silva *et al.* 2018), the bugs, *Orius insidiosus* Say and *Podisus maculiventris* Say (Assefa and Ayalew 2019; Badhai *et al.* 2020). The predatory pentatomid bugs, *Andrallus spinidens* Fabr. and *Eocanthecona furcellata* Wolff prey on the pest larvae (Keerthi *et al.* 2020). The predators, *Haematochares obscuripennis* Stal, *Pheidole megacephala* F., and *Peprius nodulipes* Signoret were found in Ghana (Koffi *et al.* 2020b). In Brazil, *O. insidiosus* is the common predator with the highest potential for use in biological control (Mendes *et al.* 2012). *O. insidiosus* and *D. luteips* showed good predation on the bigger larvae (Souza *et al.* 2021). *S. frugiperda* predators also include *Calleida decora* Fabricius, *Calosoma alternans* Fabricius, *Calosoma sayi* Dejean, *Doru taeniatum* Dohrn, *Ectatomma ruidum*- Roger, *Geocoris punctipes* Say, *Steopolybia pallipes* (Lereboullet and *P. maculiventris* (Naharki *et al.* 2020), *Cycloneda sanguinea* L., *Euborellia annulipes* Lucas, *Coleomegilla maculata* De Geer, *Hippodamia convergens* Guerin-Meneville, and *Calosoma granulatum* Perty (Prasanna *et al.* 2018; Jaraleno-Teniente *et al.* 2020).

Entomopathogens

Entomopathogenic viruses: Entomopathogenic viruses (EPVs) are effective bio-agents and eco-friendly sustainable alternatives to synthetic insecticides because of their specificity and virulence (Paredes-Sanchez *et al.* 2021). Viruses used against *S. frugiperda* include granulovirus (SfGV ARG) (Pidre *et al.* 2019), rhabdovirus (Sf-RV) (Schroeder *et al.* 2019), ascovirus (SfAV–1a) (Zaghloul *et al.* 2017), ichnovirus (HdIV) (Visconti *et al.* 2019), and baculovirus (multiple nucleopolyhedrovirus, SfMNPV) (Bentivenha *et al.* 2019). MNPV is now commercially produced and registered in many regions for *S. frugiperda* management (Haase *et al.* 2015). The baculovirus, SpliNPV is effective (60% larval mortality) against *S. frugiperda*. SpliNPV is nowadays marketed for *S. frugiperda* bio-control (Popham *et al.* 2021). Junonia coenia densovirus (JcDV) could infect *S. frugiperda* larvae orally by binding to the peritrophic matrix of the pest midgut through interaction with different glycans (Pigeyre *et al.* 2019). JcDV caused mortality to the 2nd larval instars, and it has the potential as a bio-agent candidate to control *S. frugiperda* (Chen *et al.* 2021b). Novel partiti-like viruses; SEIV1 and SEIV2 were efficiently transmitted by microinjection in *S. frugiperda* (Xu *et al.* 2020). SfMNPV is the major viral candidate used nationwide as bio-agent against *S. frugiperda*. Many SfMNPV isolates have caused high larval mortality rate (Popham *et al.* 2021). SfMNPV and SfGV are associated with the pest in the USA (Popham *et al.* 2021). The natural occurrence of some field isolates of SfMNPV were recorded in newly infested regions like India, China (Lei *et al.* 2020), and Nigeria (Wennmann *et al.* 2021). Isolates of SfMNPV that produced commercially have been successfully involved in the management of *S. frugiperda* in America, and recently in many regions in Africa and Asia (Bateman *et al.* 2021). Bioassay experiments showed that the C-strain indicated a higher susceptibility to SfMNPV isolates compared to R-rice strain, and it found that the SfMNPV isolates (459 and 1197) are fast killing isolates of the small larvae (Popham *et al.* 2021). Furthermore, SfMNPV is successfully included in IPM programs in combination with other management tactics such as spinosad (Figueroa *et al.* 2015), *Bt.* sprays (Guido-Cira *et al.* 2017), and *Bt.* transgenic plants (Farrar *et al.* 2009). Mixtures of SfCol and SfGV-VG008 or NPV and GV were very effective in controlling the 2nd larvae of *S. frugiperda* (Cuartas *et al.* 2019).

Entomopathogenic nematodes (EPNs): The EPN, *Hexamermis sp.* was recorded in Senegal parasitizing *S. frugiperda* (Tendeng *et al.* 2019). The EPNs of the genus *Steinernema* associated with the symbiotic bacterium, *Xenorhabdus* are capable of killing *S. frugiperda* (Viteri *et al.* 2018). Both the nematode and the bacterium cause insect death (Chang *et al.* 2019). The EPN, *Steinernema carpocapsae* Weiser enters the hemocoel of the pest *via* the intestinal tract and releases its symbiotic bacterium, *Xenorhabdus nematophila* Poinar and Thomas, thus it was effective against *S. frugiperda* 72 h post infestation with larval mortality of 92% (Huot *et al.* 2019).

Entomopathogenic fungi and bacteria: The entomopathogenic fungi (EPF), *Metarhizium anisopliae* Metschnikoff and *Beauveria bassiana* Bals.-Vuill showed high efficiency against the pest eggs and 2nd larval instar in the laboratory. *B. bassiana* indicated mortality of 30% against the 2nd larvae, whereas *M. anisopliae* provided 87% and 97% of egg and larvae mortality, respectively (Komivi *et al.* 2019). Natural infestation of the EPF, *Nomuraea rileyi* Farlow of 18% was found on the pest (Mallapur *et al.* 2018), and 15% (Sharanabasappa *et al.* 2019). *N. rileyi*, *M. anisopliae*, and *B. bassiana* have been suggested as the best option as bio-agents for the pest (Naharki *et al.* 2020; Bateman *et al.* 2021). *M. anisopliae* or *B. bassiana* are commercially available in Africa (Bateman *et al.* 2018). *M. anisopliae* was utilized in Rwanda, Uganda, Kenya, and Tanzania, while *B. bassiana* was used in Tanzania, Rwanda, and Uganda (Niassy *et al.* 2021).

The entomopathogenic bacterium (EPB), *Bacillus thuringiensis* (*Bt.*) Berline has been suggested as the best bio-agent for several pests including *S. frugiperda* (Al-Dababseh *et al.* 2014; Bateman *et al.* 2021). In several African countries, a number of bacteria species are commercially available, *i.e.*, *Bt.. var. Kurstaki* and *Bt. var. Aizawai* (Bateman *et al.* 2018). *Bt.. alesti*, *Bt. darmstadiensis*, *Bt. kurstaki* and *B. cereus* are tested against the pest (Naharki *et al.* 2020). *B. thuringiensis* has been produced at low cost in local production in Cuba and Brazil (Hruska 2019), and it was used in Tanzania, Uganda, and Kenya against the pest (Niassy *et al.* 2021). *S. frugiperda* mortality treated with *Bt..* was over 90% (Santos *et al.* 2021).

Botanical control using plant extracts

Compared to synthetic insecticides, the use of plant extracts is eco-friendly management approach because of their short persistence, and repellent or anti-feeding actions (Bhusal and Chapagain 2020). The use of plant extracts against *S. frugiperda* is considered efficient, cost effective, and safe for humans and the environment (Paredes-Sanchez *et al.* 2021). Azadirachtin (neem) and pyrethrins (pyrethrum) are registered products against the pest (Badhai *et al.* 2020; Bateman *et al.* 2021). Seven plant extracts have shown potential in controlling *S. frugiperda* with mortality >75% 72 h post application: *Azadirachta indica* A. Juss., *Phytolacca dodecandra* L'Her., *Croton macrostachyus* Hochst. ex Delile, *Melia curcas* L., *Melia abyssinica* L., *Schinus molle* L., *Jatropha curcas* L., and *Millettia ferruginea* Hochst. (Sisay *et al.* 2019a). In the contact toxicity traits, larval mortality of 66% was reported from extracts of *Lippia javanica* Spreng and *Nicotiana tabacum* L. (Phambala *et al.* 2020). *Cassia nigricans* Vahl extracts caused a reduction of 13% of the pest infestation on maize in Burkina Faso (Kambou and Millogo 2019). It was found that azadirachtin affects the feeding behavior of the pest (Lin *et al.* 2021). *Argemone ochroleuca* Lindl. extracts caused mortality to the larvae indicating feeding reduction and slow growth of the larvae (Martinez *et al.* 2017). Souza *et al.* (2010) reported that the oil extract of *Corymbia citriodora* Hooker has protected maize from *S. frugiperda*. *Carica papaya* L. extract caused significant larval mortality equal to that one caused by the insecticide, malathion (Brito *et al.* 2013). Extracted oils from palmarosa, clove, and turmeric showed significant efficiency against the 1st and 2nd larval instars of *S. frugiperda* (Barbosa *et al.* 2018). Extracts of *Ageratum conyzoides* L., *Ruta graveolens* L., *Bacharis genistelloides* Lam., *Cymbopogon citratus* Stapf, *Petiveria alliacea* L., *Malva sylvestris* L., *Zingiber officinale* L., *Chenopodium ambrosioides* L. and *Artemisia verlotiorum* Lamotte had insecticidal effects against *S. frugiperda* (Sisay *et al.* 2019b; Rioba and Stevenson 2020). It was found that the oil of neem seed served as efficient the synthetic insecticide, emamectin benzoate in *S. frugiperda* control (Babendreier *et al.* 2020). Delgado-Caceres and Gaona-Mena (2012) reported 82% mortality of *S. frugiperda* larvae with *Polygonum hydropiperoides* Michx extracts. *Vernonia amygdalina* Delile, *A. indica* and *Capsicum annuum* L. were used against *S. frugiperda* (Houngbo *et al.* 2020). *Citrus sinensis* L. and *Citrus limonia* L. extracted have a strong antifeedant effects against *S. frugiperda* (Jimenez *et al.* 2013).

Genetically modified crops

Genetically modified plants have been developed to control *S. frugiperda* (Machado *et al.* 2020). Genetically, *Bt.* maize is considered one of the most common effective approaches to suppress *S. frugiperda* in Brazil and the USA (Deshmukh *et al.* 2021). Transgenes that have different modes of actions such as Cry+Vip genes, could have more efficacy and sustainable control as compared to single-gene deployment (Deshmukh *et al.* 2021). Several crystal protein genes including cry1A, cry1Ab, and cry1F against *S. frugiperda* have been commercialized from *Bt.* (Horikoshi *et al.* 2016). Significant mortality of the pest larvae was noticed in *Bt.*2 maize (Montezano *et al.* 2018). *Bt.* maize expressing Cry1A.105+Cry2Ab2, Cry1F and Cry1Ab proteins were efficiently used against *S. frugiperda* management in the USA and Canada (Reay-Jones *et al.* 2016). In Africa, maize expressing Cry1A.105 + Cry2Ab2 or Cry1Ab showed resistance against *S. frugiperda* larvae (Botha *et al.* 2019). The lower larval mass fed on *Bt.*1 maize is attributed to the inhibition of growth, indicating that the pest is still susceptible to Cry1Ab (Botha *et al.* 2019). Bernardi *et al.* (2016) recorded complete mortality of the pest fed on Cry1A.105+Cry2Ab2 maize, and concluded that the pest is completely susceptible to these proteins. Ingber *et al.* (2017) showed that the larvae of C-strain are less susceptible to *Bt.* (Cry1F) than R-strain larvae. Field studies indicated that Cry1Ab maize showed a partial control of the fall armyworm in Africa (Prasanna *et al.* 2018). The susceptibility of *S. frugiperda* to toxins Cry1Ab, Cry2Ab, Cry1Fa, and Vip3Aa has been studied (Boaventura *et al.* 2020). Larvae that survived on Vip3Aa20 maize grains did not gain weight after feeding (Eghrari *et al.* 2022).

Host plant resistance

The use of plant resistant cultivars to control pests is an important management tactic because it is effective, safe for humans and the environment, and a main component of IPM (Al-Zyoud *et al.* 2009, 2015; Ghabeish *et al.* 2014, 2021). Molecular biology tools could provide a high potential for accelerating the development of promising cultivars that could provide resistance to *S. frugiperda* (Deshmukh *et al.* 2021). In this regard, maize germplasm with native genetic resistance to *S. frugiperda* was developed (Prasanna *et al.* 2018). Among 10 sweet corn genotypes, MG 161, Doce Flor da Serra, Teea Dulce, Tropical Plus, and Doce Cubano were tending to have resistance mechanisms against *S. frugiperda* due to slow insect development (Crubelati-Mulati *et al.* 2020). Sanches *et al.* (2019) observed that Zapalote Chico is less preferred by *S. frugiperda* than the other tropical popcorn genotypes. The peanut cultivars; IAC 22 and Runner IAC 886 were the least preferred ones by the insect, indicating resistance to *S. frugiperda* (Jesus and Godoy 2011). The sorghum genotype, Agromen 50A40 showed less attractiveness by *S. frugiperda* (Oliveira *et al.* 2019). In Brazil, among 12 chickpea genotypes, BRS Cicero, Nacional 27, and Nacional 29, indicated a type of resistance to the fall armyworm (Correa *et al.* 2021).

Conclusions and future perspectives

To sum up, within a short period of 6 years (since 2016), *S. frugiperda* has spread from America into many countries in Africa, Asia, Europe, and Australia, causing serious damage to crops, especially maize, reducing the global food production, and the income of million growers. In addition to early monitoring, environmentally sustainable *S. frugiperda* control needs effective integration of many approaches in IPM program. It is recommended to increase awareness among growers, people, researchers, governmental and non-governmental organizations, and decision makers about the economic importance of *S. frugiperda* nationwide. Upon this review article, the most effective methods to control the pest are found to be the use of pheromone traps, entomopathogens (nematodes, viruses, fungi, and bacteria), and genetically modified plants. Future studies should be focused on plant resistant cultivars and predators to be used against the pest.

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Author Contributions

All the four authors contributed equally in searching for the literature, and wrote the first draft of the manuscript. FA read further and improved the final draft of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

Ethics Approval

Not applicable in this paper

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