Vol. 17(9), pp. 1237-1248, September, 2021
DOI: 10.5897/AJAR2021.15666
Article Number: 5EF798C67811
ISSN: 1991-637X
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African Journal of Agricultural Research

Full Length Research Paper

Fall armyworm, *Spodoptera frugiperda* (Lepidoptera, Noctuidae): State of knowledge and control methods

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Received 11 June, 2021; Accepted 3 August, 2021

The objective of this article is to review the knowledge on *Spodoptera frugiperda* and the possible management strategies against the pest to identify research areas for its integrated management. A review of the literature shows that *S. frugiperda* (Lepidoptera: Noctuidae) has been causing considerable damage to maize and many other crops since its detection in several African countries and it is one of the most destructive pests to have entered Africa in the 21st century. Several control methods have been developed against this pest ranging from the use of synthetic plant protection products to agroecological and biological controls. The biology, distribution and control methods of the pest are well documented. However, Integrated Management of the pest remains a major challenge; the main control is chemical. Innovative research on biological and ecological control methods will help to overcome the constraints and promote sustainable management of the pest. Very few scientifically proven alternatives adapted to the African context exist. This gap needs to be filled by further research considering aspects such as the inventory of local natural enemies, the performance of key parasitoids and the potential of local entomopathogens for sustainable and integrated management of the pest.

Key words: *Spodoptera frugiperda,* natural enemies, integrated management.

INTRODUCTION

Spodoptera frugiperda (Lepidoptera: Noctuidae) is a lepidopteran pest, native to the Americas, attacking more than 80 species of crops and has found its way to Africa causing much economic damage to crops especially maize (Prasanna et al., 2019). Tens of millions of smallholder farmers in Africa are affected by the pest as its host plants including Poaceae (maize, sorghum and millet) are all staple crops in Africa (Day et al., 2017). *Spodoptera frugiperda* is therefore a major threat to food security and a serious problem from an economic and environmental perspective (Tambo et al., 2017). Since the invasion by the pest, much investment has been made in synthetic chemicals which use remains the main recourse of farmers (Kumela et al., 2018). Other

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sustainable methods represent better alternative for vulnerable producers with limited resources (Thierfelder et al., 2018). However, little recommendable empirical evidence is available for effective and more sustainable management of the pest in Africa, as most of the existing information is based on studies in the Americas (Baudron et al., 2019). This article reviews the state of knowledge on the fall armyworm and also takes stock of some of the pest control work conducted around the world to serve as a crucible of systematised information and to draw probable avenues of research for a more integrated management of the pest in Africa.

METHODOLOGY

For this review, the search engines *Google Scholar, ScienceDirect* and the Electronic Scientific Information Base (AGORA) were consulted. Literature searches were carried out by entering key words and phrases in the aforementioned search engines. Several keywords or topical statements have been used in this context (Table 1). This first step allowed the identification of a very wide range of documents which were thereafter summarized and analyzed following a systematic sorting. The titles and/or abstracts of the works were examined to eliminate those that did not fit precisely with the objective of the study. This sorting made it possible to retain 300 relevant documents including scientific articles, master's theses, doctoral theses, conference proceedings, book chapters on the theme and others published until March 2021. Our documentary research also led us to the libraries of Benin universities and other specialized institutions at the national, regional and international levels. All the documents selected were then subject to in-depth analysis and extraction of data used in this review.

Origin and distribution

Spodoptera frugiperdais native to tropical and subtropical regions of the Western Hemisphere of America, from the United States to Argentina (Cokola, 2019). It is commonly found in the Caribbean, including Puerto Rico (Capinera, 2001). In 2016, *S. frugiperda* was reported for the first time in West Africa (Cock et al., 2017; Goergen et al., 2016). By the end of 2017, the pest had spread to more than 30 countries across tropical and southern Africa as well as Madagascar, Seychelles, and Cape Verde with definite potential to spread to parts of the Mediterranean Asia and Australia (Day et al., 2017). Through the use of an environmental suitability index, the distribution of *S. frugiperda* has been modeled across the African continent (Figure 1) and currently over 44 countries are affected in sub-Saharan Africa (Day et al., 2017). *S. frugiperda* has also been reported in Asia, specifically in India since 2018 (Shylesha et al., 2018; Kalleshwaraswamy et al., 2018).

Description and biology

Insects belonging to the order Lepidoptera are those with complete metamorphosis with variable cycles including 4 stages namely egg, larvae, pupa and adult (Cokola, 2018). For *S. frugiperda,* the complete cycle is on average 30 days when conditions are dry (25±1°C and 70±10% relative humidity), and favorable for its growth and development (Busato et al., 2005). However, this cycle can extend to 60 days in spring and autumn and 80 to 90 days in winter without diapause (Capinera, 2014; Prasanna et al., 2018).

Egg stages

The egg of *S. frugiperda* is dome-shaped with a flattened base, curving upwards to a strongly rounded point at the top (Prasanna et al., 2018). It measures about 0.4 mm in diameter and 0.3 mm in height (Luginbill, 1928; Capinera, 2014). The fecundity per life cycle of a female *S. frugiperda* ranges from 1500-2000 (Prasanna et al., 2018). Females may or may not cover the laid eggs with fluffy material or self-silks to protect them (Hardke et al., 2015; Du Plessis et al., 2018). The number of eggs per mass varies between 150 and 200 with an egg stage duration ranging from 2 to 3 days during the hot summer months (Prasanna et al., 2018). Eggs may be cream, green or brown, but turn black after development of an embryo (Capinera, 2001). The different stages of the development cycle of *S. frugiperda* are illustrated in Figure 2.

Larval stage

S. frugiperda has six larval instars from hatching and the appearance as neonates, lasting 14 days during warm summer months and 30 days during the period of low temperature (Prasanna et al., 2018). The duration of the larval stage is influenced by a combination of factors including temperature and feeding (Hardke et al., 2015). The width of the head capsules varies from about 0.35 to 2.6 mm respectively for instars one to six with a size reaching about 1.7 to 34.2 mm during the six successive instars (Capinera, 2001). The raised spots, usually dark coloured with spines, are observed dorsally on the body of the mature larva (Visser, 2017; Prasanna et al., 2018). It is also possible to find two colours (orange and black) on the head from the third larval instar onwards (Capinera, 2002). This variation in colours at the last three larval instars is a function of diet and other factors (Hardke et al., 2015). In the terminal stage, the larval epidermis is rough or granular in texture when examined closely (Kalleshwaraswamy et al., 2018). At this stage, *S. frugiperda* larvae can be identified by some characteristic features (Figure 3) namely four large spots arranged in a square on the upper surface on the eighth abdominal segment and a white inverted "Y" mark on the head (Prasanna et al., 2018).

Pupal stage

The pupal stage of *S. frugiperda* is often found in shaded, hidden areas or in leaf debris and soil at a depth of 2-8 cm (Luginbill, 1928; Capinera, 2001). The cocoon is reddish-brown in colour and 14-18 mm long and about 4.5 mm wide (Capinera, 2001). The duration of this stage is strongly influenced by temperature and is about 8-9 days during summer, but could extend to 20-30 days during cold periods (Prasanna et al., 2018). In *S. frugiperda*, diapause is not observed at this stage as in many species belonging to the same order (Luginbill, 1928). At the cocoon level, it is possible to distinguish between males and females from the distance between the genital opening and the anal slit; this distance being greater in females than in males (Luginbill, 1928; Kalleshwaraswamy et al., 2018).

Adult insect

Adults of *S. frugiperda* are nocturnal, most active during warm and humid evenings with an estimated lifespan of about 10 days on average or about 7 to 21 days (Prasanna et al., 2018). They measure between 32 and 40 mm with remarkable morphological differences between the sexes (Capinera, 2001). In males, the forewing is shaded, usually grey and brown, with white triangular spots at the apical area near the centre of the wing (Figure 4), while

Table 1. Keywords used for online documentary research.

Pests / predators or natural enemies	Pest managements
Spodoptera frugiperda,	integrated management + *Spodoptera frugiperda*
Natural enemies + *Spodoptera frugiperda*	Entomopathogens + *Spodoptera frugiperda*
predators + *Spodoptera frugiperda*	Metarhizium + *Spodoptera frugiperda*
Cotesia marginiventris + *Spodoptera frugiperda*	Biological controls + *Spodoptera frugiperda*
parasitoids + *Spodoptera frugiperda*	Nuclear Polyhedrosis Virus + *Spodoptera frugiperda*
Chelonus insularis + Spodoptera frugiperda	Beauveria + *Spodoptera frugiperda*
Telenomus remus + *Spodoptera frugiperda*	Ecological controls + *Spodoptera frugiperda*
Trichogramma sp. + *Spodoptera frugiperda*	Cultural controls + *Spodoptera frugiperda*
	Varietal controls + *Spodoptera frugiperda*

Source: Adjaoke (2021).

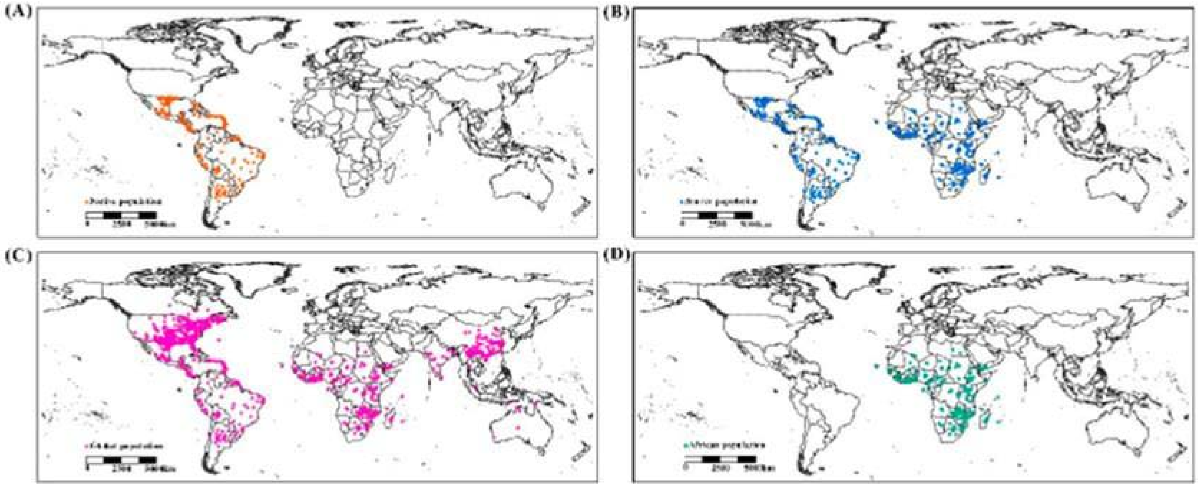

Figure 1. Geographical distribution of *Spodoptera frugiperda*. (**A**) original population, (**B) origin of** the population, (**C**) global population and (**D**) African population.
Source: Fan et al. (2020)

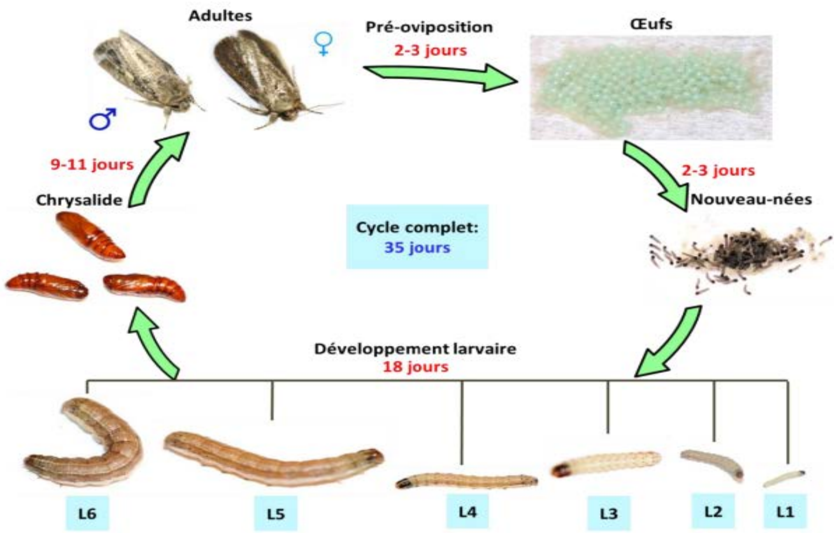

Figure 2. Development cycle of *Spodoptera frugiperda.*
Source: Cokola (2018).

Figure 3. Characteristic marks of the adult larva of *Spodoptera frugiperda.*
Source: Visser (2017).

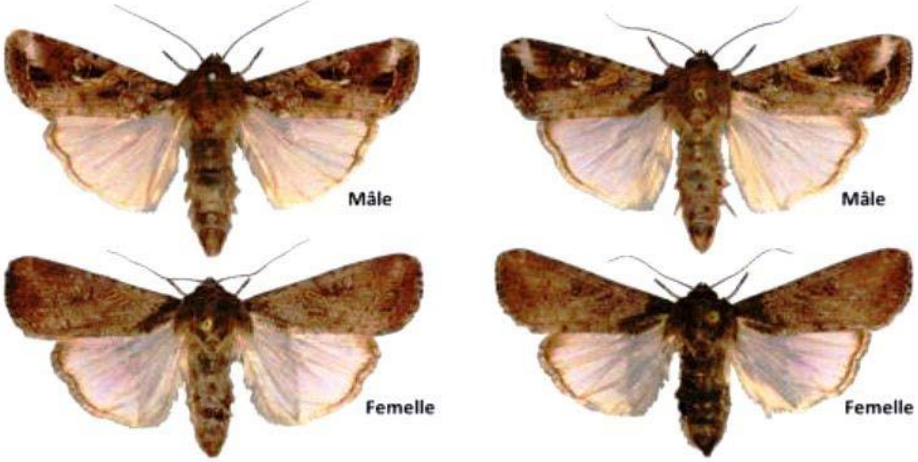

Figure 4. Patterns of wing variation in adult *Spodoptera frugiperda*.
Source: (Visser, 2017)

in females this characteristic feature is less marked, ranging from a uniform greyish brown to a fine mottling of grey and brown (Hardke et al., 2015; Shylesha et al., 2018). The hindwing is silvery-white with a narrow, dark margin in males (Figure 4) as well as in females (Kalleshwaraswamy et al., 2018). In general, adults of *S. frugiperda* feed mainly on nectar of various plants and are active for short period before sunset and during the night (Luginbill, 1928). In nature, they remain hidden under foliage and in whorls (Capinera, 2001; Visser, 2017). After 3-4 days of pre-oviposition period, the female lays most of her eggs during the first 4-5 days of her life, but with extreme cases for up to 3 weeks (Prasanna et al., 2018). A female can lay 6-10 masses of 100-300 eggs. This performance is significantly limited under laboratory conditions (Prasanna et al., 2018). Two factors that influence the longevity of adults: are feeding and temperature (Luginbill, 1928). In the laboratory, the total duration of the development cycle of *S. frugiperda* was about 39 ± 5 days (Kouakou et al., 2019). This duration was almost identical to that obtained by Schmidt-Durán et al. (2015). Indeed, these authors observed during their work that under environmental conditions marked by a temperature of 24°C, 70% relative humidity and artificial feeding, the complete life cycle of *S. frugiperda* is 38 days. Under the same conditions, the larval and chrysalis stages lasted 24 ± 5 days and 9 ± 1 day respectively, while from oviposition to hatching, the egg takes about 2 to 3 days (2.75 ± 44 days). To each developmental stage, corresponds a specific life span, weight and size (Table 2) in the pest (Cokola, 2018). Da Sylva et al. (2016) obtained a larval life span ranging from 21.41 ± 0.15 to 29.37 ± 0.5 days and a chrysalis stage duration oscillating between 8.54 ± 0.09 and 9.70 ± 0.20 days with different food supports.

Some confusion arises in the morphological identification of adult

Table 2. Characteristics of the developmental stages of *Spodoptera frugiperda*

Instar	Duration (day)	Weight (mg)	Size (mm)
Egg	2.72 ± 0.46	-	-
First larval instar	3.55 ± 0.51	0.64 ± 0.18	3.0 ± 0.0
second larval instar	1.39 ± 0.50	3.02 ± 0.88	5.2 ± 0.4
Third larval instar	1.55 ± 0.51	13.7 ± 2.39	9.2 ± 0.8
Fourth larval instar	3.16 ± 0.51	67.3 ± 10.9	13.6 ± 0.5
Fifth larval instar	2.55 ± 0.70	139.9 ± 21.8	22.4 ± 1.5
Sixth larval instar	6.05 ± 0.80	548.1 ± 73.5	34.6 ± 1.1
Pupea	10.27 ± 1.02	217.2 ± 37.1	15.4 ± 2.1
Adult	11.83 ± 0.38	129.0 ± 24.0	18.0 ± 1.2

Source: Cokola (2018).

moths of species of the genus *Spodoptera* (Cokola, 2018). This is the case of male adult of *S. frugiperda* which can be easily confused with those of *Spodoptera ornithogalli* and females, of *Spodoptera exigua* (Hardke et al., 2015). The genitalia of the males of *S. ornithogalli* are different from those of *S. frugiperda* - the double coremata lobe and the larger and wider clavus (Cokola, 2018). In *S. frugiperda,* the valve is also less wide and the female genitalia of *S. exigua* are different from those of *S. frugiperda (par)* by the elongated corpus bursae and signum (Hardke et al., 2015). Samples of entomological materials from several sources in West and Central Africa were sent for accurate diagnosis in the IITA-Benin station, where morphology the characters of immature stages and adult moths, including male and female genitalia were examined using keys for positive identification of *S. frugiperda* (Goergen et al., 2016). To confirm the identity of the species, present in Africa further, larval and adult specimens from Nigeria and São Tomé Et Príncipe were analysed by "DNA barcoding" at the Virology and Molecular Diagnostics Unit at IITA-Nigeria (Goergen et al., 2016).

Ecology

S. frugiperda is a tropical and subtropical species that adapts well to warm regions around the world (CABI, 2019). Temperature is a very important index for its growth and development (Cokola, 2019). The developmental time of eggs, larvae and pupae decreases with temperature up to 35°C (Hogg et al., 1982). Modelled data estimates made on temperature variations for growth and development of S. *frugiperda* are 12, 25, 30, 39 and 60°C for the base (minimum) temperature, lowest optimum temperature, highest optimum temperature, maximum temperature, as well as degree day, respectively (Du Plessis *et al*., 2018). Temperature minimum of 8.7°C and maximum of 39.8°C have been reported for the growth and development of *S. frugiperda* (Valdez-Torres et al., 2012). Similar temperatures were determined by López et al. (2019) with a minimum of 10.9 and 9.1°C days for the development of *S. frugiperda* with systematic mortality of all biological developmental stages of the pest at a temperature of 0°C (Luginbill, 1928). The fecundity and longevity of the adult insect are highest between 21 and 25°C (Barfield and Ashley, 1987). Rainfall, irrigation and colder annual temperatures are important variables with a direct negative effect on larval and pupal survival (Day et al., 2017).

Damage and economic importance

S. frugiperda was reported to be a destructive pest of many crops over 200 years ago (Luginbill, 1928). The larvae of *S. frugiperda* cause severe damage to all phenological stages of the plant. The caterpillar is capable of attacking 100 different plant species and 27 plant families with rapid oviposition and unimaginable proliferation, thus increasing the risks of a generalised infestation of different farms (Villa-Castoreña et al., 2004). With an unrivalled preference for maize (Day et al., 2017) which is a main staple food of the population in Sub-Saharan Africa (Ekpa et al., 2018), *S. fruigiperda* can also attack many other important crops viz sorghum, rice, sugarcane, cabbage, beet, groundnut, soybean, onion, pasture grasses, millet, tomato, crabapple and cotton (Prasanna et al., 2018). Yield losses of 15-73% are recorded when 55-100% of the plants are infested by *S. frugiperda* especially in the middle and late stages of maize development (Hruska and Gould, 1997). The larval stages of the pest appear to be much more damaging to maize in West and Central Africa than most other *Spodopteran* African species, as the larvae cause significant damage (Figure 5) on this economically important crop (Goergen et al., 2016). The responses of maize germplasm under fall armyworm infestation are measured on the Davis scale, which assesses the extent of leaf damage or ear damage compared to a susceptible control on a scale of 1 to 9 (Davis et al., 1992).

Surveillance and early warning against *S. frugiperda*

Due to its rapid spread and high capacity to cause widespread damage to several crops, the fall armyworm poses a serious threat to food and nutrition security and livelihoods of hundreds of millions of farming households in Sub-Saharan Africa (Prasanna et al., 2018). Early detection of the pest is therefore necessary through monitoring and early warning to assess accurately the level of fall armyworm infestation in the fields (Prasanna et al., 2018). Frequent observation and estimation of pest population and losses should be carried out in maize fields using suitable methods either by scouting, use of pheromone traps or light traps (Day et al., 2017). Insect captures indicate the presence of moths in the area, but may not be accurate indicators of density. Light traps can be used to monitor the adult fall armyworm, which traps both male and female insects. Monitoring is usually conducted to assess both the economic risk of pest infestation and the potential effectiveness of early and sustainable pest control interventions in fields or farms (Prasanna et al., 2019). This monitoring can be done by walking in a "W" pattern in the field with gaps of 4-5 outer rows between two points to be sampled (McGrath et al., 2018). The alert is triggered once 5% of the plant is damaged at the seedling stage (Kumbhar, 2019). Similarly, this alert should be triggered if 10 and 20% are damaged at the intermediate and late whorl stage respectively (Kumbhar, 2019).

Figure 5. Damage of *S. frugiperda on* a maize plant in South Benin.
Source: Goergen (2016).

Methods of control of *S. frugiperda*

Cultural and varietal control

Cultural practices including crop association, conservation agriculture and its components generally improve biological activity within the cropping system while limiting insect and pathogen attacks. This approach provides shelter for predators and natural enemies of *S. frugiperda* and is a means of controlling the larvae of the pest by reducing its proliferation (Prasanna et al., 2019). A study conducted in Benin revealed that about 38% of the farmers have used at least one agricultural practice for the control of *S. frugiperda* in maize fields (Houngbo et al., 2020). This study also concluded (based on assessment of farmers' perceptions) that the most common management method used by farmers was chemical control through the use of synthetic pesticides (91.4%) while only 1.9% of botanical pesticides and 6.6% of other pest control practices were used. Information on farmers' knowledge and management practices is essential for developing appropriate management methods tailored to farmers' needs (Obopile et al., 2008).

Regarding varietal control, studies conducted in the United States at the Southern Insect Control Research Unit showed that *S. frugiperda* larvae fed on Bt maize hybrids expressing the Cry1Ab protein showed a decrease in weight within 5 days of observation (Anne-Marie, 2006). This weight decrease was significantly correlated with the amount of toxin present in the plant material consumed by the larvae (Anne-Marie, 2006) In the same area, laboratory trials were conducted to compare the behaviour of *S. frugiperda* larvae fed on transgenic and conventional maize plants (Bokonon-Ganta et al., 2003). Significant differences were observed in these trials between larvae fed on transgenic and conventional maize at several levels namely survival, weight and development time of larvae and pupal stage with larval survival rates of 28-70% on the two transgenic cultivars, compared to 62-97% recorded on both the conventional cultivars and artificial diet (Bokonon-Ganta et al., 2003). Fall armyworm resistant germplasm has been developed in Mexico, USA and Brazil with a diversity of resistant varieties identified which indicated that there are many conventional traits to support a forward breeding strategy to incorporate fall armyworm resistance into the genetic elite of maize adapted to Africa (Prasanna et al., 2019). In some countries in Africa such as Cameroon, Egypt, Ghana, Kenya, Malawi, Nigeria, and Uganda, research has been conducted on resistant maize varieties that have yielded encouraging results in managing *S. frugiperda* but much work remains to be done (et al., 2018).

Control based on the use of parasitoids and predators as natural enemies

S. frugiperda has a diverse complex of natural enemies in the Americas and the Caribbean basin (Ashley, 1979; Ashley et al., 1982; Molina-Ochoa et al., 2003). In North and South America, studies revealed 53 species of parasitoids of *S. frugiperda in* 43 genera and 10 families, including Braconidae, Ichneumonidae and Tachinidae (Table 3), which accounted for 16, 19 and 47% of the genera and 15, 17 and 53% of the species in this group respectively (Ashley, 1979). Subsequently, 150 species of parasitoids and parasites of *S. frugiperda* have been reported from the Americas and the Caribbean Basin, belonging to 14 families (Table 2), namely nine in the Hymenoptera, four in the Diptera and one nematode (Molina-Ochoa et al., 2003). Ten species of Hymenoptera belonging to five families including *Telenomus remus*, recognised as a parasitoid of *S. frugiperda* eggs were tested to control *S. frugiperda* (Cokola, 2018; Hoballah et al., 2004; Gutiérrez-Martínez et al., 2012). *Chelonus insularis* (Hymenoptera: Braconidae) and *Cotesia arginiventris* (Hymenoptera: Braconidae) were identified as a result of a survey as the main parasitoids of *S. frugiperda* eggs and larvae and cited as the most abundant in north of America (López et al., 2018). Braconidae were the best represented (Table 3) with 261 specimens (21.75% of total parasitism), of which 257 were *Chelonus insularis* (21.42%),

Table 3. *Spodoptera frugiperda's parasitoids* and predators

Order	Family	Species	References
Parasitoids			
Hymenoptera	Braconidae	*Cotesia marginiventris* Cresson	Hoballah et al. (2004); 43. Hay-Roe et al (2016); Lopez et al. (2018); FAO (2018)
		Cotesia icipe	Sisay et al. (2018)
		Eiphosoma laphygmae Costa Lima	Hoballah et al. (2004); López et al. (2018)
		Chelonus insularis Cresson	Hoballah et al. (2004); Murúa et al. (2009); Rios-Velasco et al. (2011); Virgen et al. (2013); *Meagher et al. (2016);* López et al. (2018); FAO (2018)
		Homolobus truncator Say	Hoballah et al. (2004)
		Aleiodes laphygmae Viereck	Hoballah et al. (2004)
		Glyptapanteles creatonoti Viereck	Shylesha et al. (2018)
	Ichneumonidae	*Campoletis grioti* Blanchard	Murúa et al. (2009)
		Campoletis sonorensis Cameron	Hoballah et al. (2004)
		Ophion flavidus Brullé	Hoballah et al. (2004); Murúa et al. (2009)
		Campoletis chlorideae Uchida	Shylesha et al. (2018)
		Pristomerus spinator Fabricius	Hoballah et al. (2004)
		Hyposoter sp.	Virgen et al. (2013)
		Diapetimorpha introita Cresson	Molina-Ochoa et al. (2003)
		Charops ater Szépligeti	Sisay et al. (2018)
	Trichrogrammatidae	*Trichogramma atopovirilia* Oatman & Platner	Hoballah et al. (2004) ; FAO (2018)
	Eulophidae	*Euplectrus platyhypenae* Howard	Hoballah et al. (2004)
	Platygastridae	*Telenomus remus* Nixon	FAO (2018); Kenis et al. (2019)
Diptera	Tachinidae	*Archytas marmoratus* Townsend	Virgen et al. (2013); FAO (2018)
		Archytas incertus Macquart	Murúa et al. (2009)
		Incamyia chilensis Aldrich	Murúa et al. (2009)
Predators			
Coleoptera	Coccinellidae	*Coleomegilla* sp.	Hoballah et al. (2004) ; FAO (2018)
		Harmonia axyridis Pallas	FAO (2018)
		Eriopis connnexa Germar	Silva et al. (2013)
	Carabidae	*Calosoma granulatum* Perty	FAO (2018)
Dermaptera	Forficulidae	*Doru* sp.	Hoballah et al. (2004); Pasini et al. (2007); Shylesha et al. (2018); FAO (2018)
Heteroptera	Reduviidae	*Zelus longipes* Linnaeus	Hoballah et al. (2004) ; FAO (2018)
		Castolus sp.	Hoballah et al. (2004)
	Pentatomidae	*Podisus sagitta* Fabricius	Hoballah et al. (2004)
		Podisus nigrispinus Dallas	Zanuncio et al. (2008)
	Anthocoridae	*Orius* sp.	Hoballah et al. (2004)
Hymenoptera	Formicidae	*Solenopsis geminata*, Pheidole radowszkoskii	Perfecto (1991)
	Vespidae	*Polistes* spp.	Held et al. (2008)

Source: Cokola (2018).

Chelonus cautus (0.25%) and *C. sonorensis* (0.08%) (Cokola, 2018). Although *T. remus* was introduced to Brazil several decades ago, its natural occurrence in the fields has been very rare, while populations of *T. pretiosum* and/or *T. atopovirilia* are often reported (Beserra et al., 2002). Of these three species, *T. remus* has been considered the best candidate from augmentative biology, because of its ability to reach the inner layers of *S. frugiperda* egg masses (Cave, 2000). Laboratory studies have shown that *T. remus* parasitises *S. frugiperda* eggs more rapidly than *T. pretiosum* and, when the two species are brought together in an arena containing *S. frugiperda* eggs, the majority of emerged adults are of *T. remus* (Carneiro and Fernandes, 2012). However, there are no real studies exploring the interference and exploitation competition between *T. remus*, *T. atoporivilia* and *T. pretiosum* under field conditions but some work on natural enemy parasitoids of *S. frugiperda in* Africa has been carried out (Kenis et al., 2019).

A recent study on the first global modelling efforts by the fitted procedure of a machine learning algorithm to predict the habitat suitability of *S. frugiperda* and its major parasitoids namely *Chelonus insularis, Cotesia marginiventris*, *Eiphosomala phygmae*, *Telenomus remus* and *Trichogramma pretiosum*, to be considered for biological control was conducted (Tepa-Yotto et al., 2021). Modelled predictions showed establishment potentials of the five hymenopteran parasitoids of the pest in the coastal belt of West Africa from Côte d'Ivoire to Nigeria, the Congo Basin in East Africa, East Asia, Southeast and parts of Eastern Australia, and Western and Southern Europe which are areas heavily affected by the pest (Tepa-Yotto et al., 2021). Most reviews of parasitoids of *S. frugiperda* have focused on those that attack eggs and larvae (Ashley, 1986). However, there is a lack of information on the spatio-temporal distribution and determinants of better utilization of its local natural enemies in Sub-Saharan Africa. Forficulidae have been identified as important predators of *S. frugiperda* (Shylesha et al., 2018). *Eriopis connnexaa* has been identified as a potential predator for the control of *S. frugiperda* (Silva et al., 2013). Some species of Coccinellidae such as *Harmonia axyridiscan* also attack *S. frugiperda* (Dutra et al., 2012).

Control based on the use of entomopathogenic fungi

It is estimated that 750 to over 800 fungal species from more than 90 genera have been described as pathogens against different insect species (Samson and Popovic, 1988). However, only about a dozen of these entomopathogenic fungal species are available for pest management at the grower level (Hajek and St. Leger, 1994) and others are effective against a wide range of insect pests including *Spodopteran* species (Purwar and Sachan, 2005). For insect control, *Beauveria bassiana* is known to be the most common, highly effective and widespread entomopathogenic fungus worldwide (Khan and Ahmad, 2015). Ruiz-Nájera et al. (2013) isolated *Nomurae arileyi* from 38 larval corpses of *S. frugiperda*. Work revealed that the concentration of 1×10^8 conidia/ml was the most effective dose of entomopathogenic fungi (Kaur et al., 2009). Other studies in Faisalabad, Pakistan having investigated the efficacy of entomopathogenic fungi on Lepidoptera revealed that the susceptibility of insects subjected to the action of the said fungi decreases with an increase in the age of 285 larvae (Asi et al., 2013). The mortality of *S. frugiperda was* evaluated under laboratory conditions using various concentrations of conidia of a native strain and a commercial strain of *M. anisopliae* (Romero-Arenas et al., 2014). The highest mortality that is, 72.5% was recorded in the indigenous strain while 32.5% was obtained in the commercial strain whose results revealed lower efficiency compared to the indigenous strain (Romero-Arenas et al., 2014). It has been reported that all species of lepidopteran pests of vegetable crops, were susceptible to *B. bassiana* while reporting that *S. frugiperda* was the least susceptible (Wraight et al., 2010).

Control using entomopathogenic bacteria, nematodes and viruses

Among the alternatives to control *S. frugiperda*, the use of *Bacillus thuringensis* (Bt) has been the subject of interest because of its effectiveness in controlling the pest and its low impact on natural enemies (Polanczyk and Alves, 2005). Studies have shown that *Bt* affects biological parameters with a definite influence on the weight of larvae, pupae, oviposition and fecundity of *S. frugiperda* females (Polanczyk and Alves, 2005). *Bt* Cry protein has been effectively used in America for the control of *S. frugiperda* but resistance of the pest against this protein has been noted (Farias et al., 2014; Dangal and Huang, 2015). The composition, abundance and diversity of microbiomes associated with larval and adult specimens of *S. frugiperda* have been studied in Africa (Gichuhi et al., 2020) however the first data on the efficacy of *Bt for* the control of *S. frugiperda in* Africa were provided by Botha et al. (2019). Entomopathogenic nematodes (EPNs) have been used as biological control agents to control some species of the genus *Spodoptera* in the laboratory and in the field (Campos-Herrera and Gutierrez, 2008). Nematodes, grouped in two main families Steinernematidae and Heterorhabditidae are obligate parasites of some insect species and more specifically *S. frugiperda* and are associated with some symbiotic bacteria (Sree and Varma, 2015). One species each of *Steinernema* and *Heterorhabditis* have been used for the control of *S. frugiperda* with an efficiency evaluated up to 100% of larval mortality (Andaló et al., 2010). *Steinernema* and *Heterorhabditis* have been used to control *S. frugiperda* in association with some insecticides (Negrisoli et al., 2013). *S. frugiperda*, is susceptible to several entomopathogens including a nuclear polyhedrosis virus (NPV) and a Granulosis virus (GV) (Gardner and Fuxa, 1980). Research on the use of viruses as entomopathogens is focused on baculoviruses (Sree and Varma, 2015). For the control of *S. frugiperda,* Nucleo Polyhedro Viruses (NPVs) have been the most studied (Berretta et al., 1998). The Nucleo Polyhedro Virus (NPV) of *S. frugiperda* (SfMNPV) has been isolated from populations of armyworms in North, Central and South America (Berretta et al., 1998; Shapiro et al., 1991). Some isolates of this virus have been evaluated in the field as potential biopesticides to control *S. frugiperda* on maize (Moscardi, 1999) resulting in high levels of larval mortality associated with significant mortality due to natural parasitism (Armenta et al., 2003; Castillejos et al., 2002). In southern Mexico, the impact of organophosphate insecticides (chlorpyrifos, methamidophos), carbamate (carbaryl) and pyrethroids (cypermethrin) commonly used in corn fields with natural enemies of crop pests has been compared to that of 'a nucleopolyhedron (Baculoviridae) of *Spodoptera frugiperda*. The results showed a mortality rate ranging from 75 to 90% of the natural enemies after the application of these synthetic insecticides while the bioinsecticide had not induced any effect. These synthetic insecticides were applied at the rates recommended on the product label using a hand-held backpack sprayer equipped with a cone nozzle. The biological pesticide was applied at the rate of 3×10^{12} occlusions bodies (OB)/ha using identical equipment. The effects of pesticides on arthropods on corn plants were quantified at intervals of 1 to 22 days after application. The biological insecticide based on *S. frugiperda* nucleopolyhedrovirus had no adverse effect on natural enemies of insects or other non-target insect populations. Applications of carbamate, pyrethroid and organophosphate insecticides all reduced the abundance of natural enemy insects, but for a relatively short period (8-15 days) (Martinez et al., 2003).

Use of plant extracts

To limit environmental and health risks, the use of less toxic natural products, such as neem, pyroligneous and asteraceous extracts, is a sustainable alternative in agricultural areas (Charleston et al., 2005). In Brazil, experiments carried out at (25 ± 1°C) with a 12 h photoperiod and (70 ± 10%) relative humidity in the laboratory using aqueous extracts of neem and pyroligneous diluted in water (10 or 20 ml/L) and applied to freshly laid eggs of *S. frugiperda* or to day old and two-days-old eggs resulted in a reduction in their hatching rate (Tavares et al., 2009). In Ethiopia, high mortality of *S. frugiperda* was reported with extracts of *Jatropha curcas*, *Militia ferruginea*, *Phytolacca dodecandra*, *Scinus molle*, *Melia abyssinica*, *Nicotiana tabacum*, *Lantana camara*, *Chenopodiumam broides*, *Azadirachta indica*, and *Jatropha gossypifolia* (Sisay et al., 2019). Similar activities have been reported for *A. indica* and *N. tabacum* against *S. frugiperda* in Africa (Phambala et al., 2020). The most promising plant species in Africa due to their low toxicity, abundance and bioactivity against *S. frugipera* are *Lippia javanica*, *Ocimum basilicum* and *Cymbopogon citratus* which have shown various activities including decreased feeding and reproduction as well as increased mortality of the pest (Silva et al., 2013). Trials conducted under laboratory conditions on the bioactivity of plant extracts of *Calotropisprocera*, *Jatropha curcas*, *Cymbopogon nardus*, *Zyzyphus joazeiro*, Morinda *citrofolia*, and *Magonia pubescamens* generated interest in the use of their extracts because, having resulted in an increase in larval mortality and a significant decrease in the weight of *S. frugiperda* pulps (Santos et al., 2012). The results of this study showed that methanolic extracts of leaves and fruit peels, applied on *S. frugiperda* at the 2nd larval stage fed on artificial diet resulted in reduced larval growth, longer developmental time, reduced fertility as well as increased mortality of the pest (Santos et al., 2012). The *T. saponaria* extract was the most promising for the control of *S. frugiperda*, possibly because its seeds were rich in fat, yielding an equally fatty extract with adjuvant capacity thus facilitating the attachment and distribution of the extract on maize leaves, thereby increasing the insecticidal action (Santos et al., 2012). However, it remains to be determined which insecticidal compounds in these plants could lead to new natural insecticidal products that could be developed (Alves et al., 2012). This provides an opportunity for exploration and research of other plants with these compounds to incorporate them into the pool of plants that provide promising results for the management of *S. frugiperda* in Africa (Santos et al., 2012).

Chemical control methods and risks of pest resistance to molecules

Insecticidal control of *S. frugiperda* is often necessary in order to protect the crops and ensure adequate productivity (Luginbill, 1928; Straub and Hogan, 1974). The techniques used in this case are dictated by the developmental stage and growth characteristics of the host crop as well as the available insecticide application methods (Togola et al., 2018). Management of the pest requires the use of large quantities of insecticides and sometimes the use of several types and formulations of chemicals, with high environmental and health risks incurred by both producers and consumers (Togola et al., 2018). Effective application of pesticides may result in some reduction of pests, but also cause damage to beneficial insect populations thus increasing pest population pressure and crop damage (Prasanna et al., 2018).

Results of trials conducted in Mokwa, Nigeria revealed the presence of five insecticidal compounds (cypermethrin, deltamethrin, lambda-cyhalothrin, permethrin and chorpyrifos) in soil samples with possible negative effects on soil dwelling organisms and other non-target species (Togola et al., 2018). This was also detrimental to the environment, as the molecules of the products used to affect local biodiversity, environmental components, human health and pest resistance to the molecules used (Sellami et al., 2015). A strain of *S. frugiperda*, collected from a cornfield in northern Florida showed resistance to commonly used insecticides. Resistance to pyrethroids ranged from 2 to 216-fold; resistance to organophosphate insecticides ranged from 12 to 271-fold and resistance to carbamates ranged from 14 to 192-fold (Yu, 1991). The highest level of resistance was observed with carbary (Yu, 1991).

Issues related to the integrated management of *S. frugiperda*

The limitations associated with the use of synthetic plant protection products with their numerous risks to human health, the imbalance of environmental components and pest resistance (Barzman et al., 2015) impose the adoption of agroecological practices and integrated management of *S. frugiperda* as an unquestionable option in view of the speed of the pest's progression and the damage it causes to farmers (Georgen, 2016; Hay-Roe et al., 2016). The preferred management option for *S. frugiperda* is therefore Integrated Pest Management (IPM-Integrated Pest Management), based on the use of a combination of control methods that is sustainable, cost-effective and results in minimal risks to humans and the environment (Day et al., 2017).

Conclusions

The present literature review has provided an overview of updated state-of-the-art on *S. frugiperda* bioecology and management Information related to taxonomy, description, ecology, origin, damage, economic importance, dispersal of the pest and its management by agricultural chemicals is available. Similarly, a sufficient range of scientific evidence on the existence and use of natural enemies, entomopathogens and plant extracts is available. However, the literature reveals little empirical evidence to guide recommendations for effective control of *S. frugiperda* in Africa since existing work has not addressed, in a strict sense, control methods based on integrated pest management in the African context, even though this approach represents an important sustainable alternative beneficial to vulnerable small holder farmers.

LIMITATIONS AND PROSPECTS

The alternative methods to synthetic chemical inputs each have their advantages, but also some limitations. A combination of several much more integrated approaches is therefore needed to control *S. frugiperda* sustainably. The variability of the insect's susceptibility to the products used and the adverse effects of the latter on human health and the environment should imply a more specific control considering the pedoclimatic and socioeconomic conditions of the farmers. In this control in an African context where most farmers are vulnerable and uneducated, it is imperative to consider the sustainability of the choices made on the technical and operational levels. It is with this perspective that we will start work on the evaluation of the oviposition performance of key parasitoids of *S. frugiperda* and on entomopathogens of African strains in order to contribute to the integrated management of the pest. Similarly, some methods based on the valorisation of insecticidal plants and on empirical practices still in use and demonstrating their efficacy should also be tested in order to establish the scientific basis of their real efficacy on pest control and on their safe use and minimal impacts on human and environment health.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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