INTERNATIONAL JOURNAL OF MULTIDISCIPLINARY RESEARCH AND ANALYSIS

ISSN(print): 2643-9840, ISSN(online): 2643-9875

Volume 05 Issue 07 July 2022

DOI: 10.47191/ijmra/v5-i7-01, Impact Factor: 6.261

Page No. 1591-1601

Literature Review on the Natural Enemies of Spodoptera Frugiperda J. E. Smith (Lepidoptera: Noctuidae) and the Effectiveness of Their Use in the Management of This Pest in Corn (Zea Mays L.)

Manguilibè Tchao[1], Agbéko Kodjo Tounou[1], Komi Agboka[1], Gnon Tchein[1], Tchegueni Matotiloa[1], Atama Gnamkoulamba[1,2], Komla Sanda[3]

[1]Laboratoire de Recherche sur les Agroressources et Santé Environnementale (LARASE), Ecole Supérieure d'Agronomie (ESA), Université de Lomé (UL)

[1,2]Institut National de Formation Agricole (INFA) de Tové

[3] Université de Kara

ABSTRACT: The fall armyworm *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae) is an important maize pests that threaten food security in sub-Saharan Africa. In order to evaluate the diversity of natural enemies and especially their effectiveness for a sustainable management of this pest in Africa, a literature review was carried out. It consisted in exploiting 35 scientific publications from the most highly rated journals, over the period 2015-2020 relating to the inventory of the natural enemies of S. frugiperda and their effectiveness in the world in general and more particularly in Africa. It emerges from this study that there is a large diversity of natural enemies of *S. frugiperda* in the world. In total, 66 species of natural enemies belonging to 21 families in 10 orders have been recorded. Parasitoids have been the most studied 43 (64.18%) and the most used in the control of *S. frugiperda*, followed by predators 13 (19.40%) and entomopathogens (13.42%). In Africa, 24 of the 67 species have been recorded in 9 countries. Parasitoids were also created with a rate of 26.86% or 75.00% at the African level. The main most effective parasitoids were *Telenomus remus* (Hymenoptera: Scelionidae), *Chelonus insularis* Cresson (Hymenoptera: Braconidae) and *Cotesia marginiventris* Cresson (Hymenoptera: Braconidae) with parasitism rates varying between 0.85 and 9.90% depending on the environments. In view of the results, since these species have been listed in Africa, they seem to be real candidates for future programs for the sustainable management of this caterpillar. Research is underway in Togo and probably in the rest of the countries of the continent for a better knowledge and development of these natural enemies.

KEYWORDS: Corn, *S. frugiperda*, natural enemies, efficacy.

I. INTRODUCTION

The harmful consequences of chemical pesticides on human health and on the balance of the various ecosystems are no longer in doubt [1]. The issues of pollution, loss of biodiversity and diseases linked to the use of plant protection products are becoming increasingly alarming [2]. Since the dawn of time with the industrial revolution, the use of chemicals to control crop pests has always been controversial. Cereals, and in particular corne, are the staple food of sub-Saharan populations [3]. Since 2016, an exotic caterpillar *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae) has emerged, reducing maize production by 15-73% and thus posing a serious threat to global food security [4]. In order to achieve the Sustainable development goals, which call for the preservation of biodiversity [5], environmentally friendly control methods are increasingly being promoted in various biodiversity management programmes. Much research has been done and more is underway to sustainably manage pests with bio-pesticides. Genetic improvement for pest control is controversial in terms of ethics under the 1992 Rio Convention on Biological Diversity, but also in terms of the loss of intrinsic values of wild varieties. A study by [6] on two corn varieties showed that the new varieties were less resistant to *S. frugiperda* due to the loss of resistance genes during the crossing process. There is a range of techniques to manage this caterpillar but the sustainable management strategy is one that includes the use of natural enemies [7]. Natural enemies are therefore alternatives to chemicals against *S. frugiperda* but also a technique to support environmental protection and the sustainability of agroecosystems [8]. Several investigations have been carried out on this topic in the USA, where the insect originates [9, 10], in Mexico and Central America [11] and in Latin America [12, 13]. Although recognised as effective, pest management using natural enemies remains a vast area of instigation in sub-Saharan Africa. There is very little knowledge that can constitute a reliable database on the use of natural enemies in pest management over the last five years worldwide and more particularly in Africa. This study aims to summarise the work done on the main natural enemies of *S. frugiperda* and especially on their effectiveness in the management of this pest in the world in order to lay the foundations for sustainable biological control in Africa.

II. MATERIALS AND METHODS

A. Source of Information

The need to develop sustainable management methods for *S. frugiperda*, has led to recent bibliographic syntheses on the inventory of natural enemies of this pest and especially on tests to evaluate their effectiveness in influential journals. The research focused on the collection of relevant information from 35 published scientific articles, from bibliographic references on the inventories of natural enemies of *S. frugiperda* and their efficacy on the pest, and also from articles and abstracts of scientific papers. The synthesis was inspired by the methodology used by [11] in the USA to make a synthesis on parasitoids and parasites of *S. frugiperda*. They identified and analysed the literature related to the inventory of natural enemies of *S. frugiperda* and tests to evaluate their level of parasitism. Based on the work of [11], the methodological approach of the present paper, which focuses on the period 2015-2020, pays attention to the careful choice of the keywords to be inserted in the search engines so as not to lead to works significantly far from the main meaning of the subject. The approach was adopted by using mainly the following words and phrases: "natural enemies", "*S. frugiperda*", "parasitism rate", "efficiency". Publications mainly from journals such as "Florida entomologist", "Biological control", "Journal of insect science", "Elsevier", "PLOS ONE" and "Economic Entomology" were used for this synthesis.

B. Information's Organisation

Various information was obtained on the natural enemies of *S. frugiperda* in the world in general and in Africa in particular and is presented in Table 1. The information is presented in Table 1. It covers, in order, parasites and parasitoids of S. frugiperda, predators, entomopathogenic fungi, bacteria and viruses. For each of the natural enemies, information such as: classification, country in which it was reported and the reference of the article are reported. Then the results on the effectiveness of the main natural enemies were presented. These results were also discus, according to the study environments.

The approach was therefore to make a comparative study of the diversity of natural enemies in Africa and in the world. The efficiencies of the main natural enemies were then assessed in order to give some guidance on the possible potential of natural enemies at the African level.

III. RESULTS

A. Management of S. Frugiperda in Togo

In Togo as in most African countries, several investigations in recent years have focused on the management of *S. frugiperda*. [14], found molecular similarity between *S. frugiperda* genes from Togo and those from the Americas and the West Indies. In the perspective of sustainable management, efficiency tests of different pheromone traps were carried out in Togo [15]. The latter evaluated both the effectiveness of three different types of pheromone traps in terms of sensitivity, specificity and cost. Nowadays, contrary to the countries where the insect originates, no more information about natural enemies and even less about their effectiveness in the African context and more particularly in Togo. [16], showed that although *S. frugiperda* infestations seem to be gradually decreasing from 2016 to 2018, they remain high in Togo compared to Ghana. Hence the need to shed light on all the work done on the inventory of *S. frugiperda* natural enemies and especially their efficacy during the period 2015-2020.

B. Summary of the Main Natural Enemies Recorded

The inventory of the main natural enemies of S. frugiperda during our synthesis period resulted in the identification of numerous natural enemies of *S. frugiperda* (Table 1). All the natural enemies recorded were divided by order of representation into 10 main orders: Hymenoptera, Diptera, Coleoptera, Dermaptera, Heteroptera, Hypocreales, Nematoda. The different results are presented in the following order: parasites and parasitoids, predators and entomopathogens

Table 1. SUMMARY of NATURAL ENEMIES of *S. FRUGIPERDA* RECORDED WORLDWIDE DURING the PERIOD 2015-2020

TYPE of NATURAL ENEMY	ORDER and FAMILY	COUNTRY of COLLECTION	CULTURE	REFERENCE
1-Parasits and Parasitoids				
Chelonus bifoveolatus Szpligeti	Hymenoptera: Braconidae	Ghana, Senegal, Benin	Corn	[17] ; [18] ; [16]
Ch. insularis Cresson	Hymenoptera: Braconidae	Mexico, Florida, Tanzania, India	Corn, Sorghum	[19]; [10] ; [20] ; [21] ; [22] ; [23]; [24]
Ch. curvimaculatus Cameron	Hymenoptera: Braconidae	Kenya	Corn	[25]
Ch. formosanus Sonan	Hymenoptera, Braconidae	India	Corn	[24]
Meteorus arizonensis Muesebeck	Hymenoptera: Braconidae	Mexico, Florida	Corn	[19] ; [10]
M. laphygmae Viereck	Hymenoptera: Braconidae	Mexico	Corn	[20]
Microplitis manilae Ashmead	Hymenoptera: Braconidae	India	Corn	[24]
Coccygidium luteum Brullé	Hymenoptera: Braconidae	Benin, Ghana, Mozambique	Corn	[17] ; [26] ; [16]
Bracon sp.	Hymenoptera: Braconidae	Ghana	Corn	[16]
Cotesia icipe Fernandez,	Hymenoptera: Braconidae	Benin, Ghana, Ethiopia	Corn	[17] ; [25] ; [16]
C. ruficrus Haliday	Hymenoptera: Braconidae	India	Corn	[27]
C. marginiventris Cresson	Hymenoptera: Braconidae	Florida, Tanzania, India	Corn	[10]; [20]; [23]; [24]
Meteoridea testacea Granger	Hymenoptera: Braconidae	Ghana, Benin	Corn	[17]; [16]
Glyptapanteles creatonoti Viereck	Hymenoptera: Braconidae	India	Corn	[28]
Aleiodes laphygmae Viereck	Hymenoptera: Braconidae	Florida	Corn	[10]
Coccygidium melleum Roman	Hymenoptera: Braconidae	India, Tanzanie	Corn	[29]; [23]
Campoletis sonorensis Cameron	Hymenoptera: Ichneumonidae	Mexico, Senegal	Corn	[19]; [18]
C. flavicincta Ashmead	Hymenoptera: Ichneumonidae	Mexico	Corn	[19]
Charops sp.	Hymenoptera: Ichneumonidae	Benin, Ghana	Corn	[17]
Pristomerus sp	Hymenoptera: Ichneumonidae	Mexico	Corn	[19]
Ophion flavidus	Hymenoptera: Ichneumonidae	Florida	Corn	[10]
Metopius discolor Tosquinet	Hymenoptera: Ichneumonidae	Ghana	Corn	[17]
M. rufus Ashmead	Hymenoptera: Ichneumonidae	India	Corn	[24]
Netelia sp.	Hymenoptera: Ichneumonidae	India	Corn	[24]
Ichneumon promissorius Erichson	Hymenoptera: Ichneumonidae	India	Corn	[24]
Pristomerus pallidus Kriechbaumer	Hymenoptera: Ichneumonidae	Benin	Corn	[17]
Euplectrus platyhypenae Howard	Hymenoptera: Eulophidae	Mexico, Florida	Corn	[19]

Anatrichus erinaceus Loew	Diptera: Chloropidae	Ghana	Corn	[16]
Eucelatoria bryani	Diptera: Chloropidae	Mexico	Corn, Sorghum	[21]
Exorista sorbillans Wiedemann	Diptera: Tachinidae	India	Corn	[29]
Drino quadrizonula Thomson	Diptera: Tachinidae	Benin, Ghana, Mozambique	Corn	[17] ; [26]
Archytas marmoratus Townsend	Diptera: Tachinidae	Mexico	Corn	[19]
Lespesia sp.	Diptera: Tachinidae	Mexico	Corn	[19]
Une brachycère non identifiée	Diptera: Tachinidae	Ghana	Corn	[16]
Eriborus sp.	Hymenoptera: Ichneumonidae	India	Corn	[10] ; [29]
Campoletis sp.	Hymenoptera: Ichneumonidae	Senegal	Corn	[18]
C. chlorideae Uchida	Hymenoptera: Ichneumonidae	India	Corn	[28], [29]
Metopius rufus Ashmead	Hymenoptera: Ichneumonidae	India	Corn	[24]
Odontepyris sp.	Hymenoptera: Bethylidae	India	Corn	[29]
Telenomus remus	Hymenoptera: Scelionidae	South Africa, Benin, Ivory Coast, Niger, Kenya, Mexico, China	Corn, Sorghum	[21] ; [30] ; [31] ; [25]
Telenomus sp.	Hymenoptera: Platygastridae	India	Corn	[28]
Trichogramma sp.	Hymenoptera: Trichogrammatidae	India	Corn	[28]
Trichogramma atopovirilia Oatman and Platner	Hymenoptera: Trichogrammatidae	Mexico	Corn, Sorghum	[22]
Hexamermis cf. albicans Siebold	Mermithida: Mermithidae	India	Corn	[24]
2-Prédators				
Pheidole megacephala	Hymenoptera: Formicidae	Ghana	Corn	[16]
Haematochares obscuripennis Stål,	Heteroptera: Reduviidae	Ghana	Corn	[16]
Peprius nodulipes Signoret	Heteroptera: Reduviidae	Ghana	Corn	[16]
Cosmolestes sp.	Heteroptera: Reduviidae	India	Corn	[24]
Forficula sp.	Dermaptera: Forficulidae	India	Corn	[28] ; [29]
Harmonia octomaculata Fabricius	Coleoptera: Coccinellidae	India	Corn	[29]
Coccinella transversalis Fabricius	Coleoptera: Coccinellidae	India	Corn	[29]
Doru sp.	Dermaptera : Forficulidae	Mexico	Corn, Sorghum	[22]
Eocanthecona furcellata Wolff	Hemiptera: Pentatomidae	India	Corn	[24]
Andrallus spinidens Fabricius	Hemiptera: Pentatomidae	India	Corn	[24]
Podisus maculiventris	Hemiptera: Pentatomidae	India	Corn	[24]

Ropalidia brevita	Hymenoptera: Vespidae	India	Corn	[24]
Polistes cf. olivaceus	Hymenoptera: Vespidae	India	Corn	[24]
3- Nematode				
Hexamermis sp.	Nematoda : Mermithidae	Senegal	Corn	[18]
Ovomermis sinensis	Nematoda: Mermithidae	China	Corn	[32]
4-Fungi				
Beauveria bassiana	Hypocreales: Cordycipitaceae	Mexico, India	Corn	[19] ; [33] ; [24]
Metarhizium anisopliae	Hypocreales: Clavicipitaceae	Mexico, India	Corn	[19] ; [33] ; [24]
M. rileyi (Farl.)	Hypocreales: Clavicipitaceae	Kenya	Corn	[34]
Nomuraea rileyi (Farl.) Samson	Hypocreales: Clavicipitaceae	India	Corn	[28]; [29]
5- Virus				
SfMNPV		Mexico, India	Corn	[35] ; [19]; [24]
SfGV ARG.		Argentina	Corn	[36]
6- Bacteria				
Bacterial 16S rRNA gene.		Kenya	Corn	[34]

1) PARASITS and PARASITOIDS of S. FRUGIPERDA*:* Parasits and parasitoids represent the most important natural enemy of *S. frugiperda* among all other groups both in number and in species. Forty-three (43) parasitoids have been reported worldwide. [19], in their work in Mexico reported the presence of *Chelonus insularis* Cresson and *Meteorus arizonensis* Muesebeck (Hymenoptera: Braconidae); Campoletis sonorensis Cameron, *Pristomerus* sp. and *C. flavicincta* Ashmead (Hymenoptera: Ichneumonidae); *Euplectrus platyhypenae* Howard (Hymenoptera: Eulophidae); *Archytas marmoratus* Townsend and *Lespesia* sp. (Diptera: Tachinidae) on Corn. [10] reported in their work during the period of 2010-2015 in three countries of South Florida, two main parasitoids of *S. frugiperda* eggs on Corn crop which are *Cotesia marginiventris* Cresson (Hymenoptera: Braconidae) and *C. insularis*. The work of [20] in northern Sinaloa focused on *Meteorus laphygmae* Viereck (Hymenoptera: Braconidae), *C. insularis* and *C. marginiventris* as the most abundant parasitoids. The work of [21] and [22] has confirmed the presence of *C. insularis* in some areas of Mexico. These investigations also identified *Telenomus remus* (Hymenoptera: Scelionidae) *Trichogramma atopovirilia* (Hymenoptera: Trichogrammatidae) and a Diptera *Eucelatoria bryani* (Diptera: Chloropidae) on corn and sorghum.
In Asia, research by [28] identified parasitoids such as *Glyptapanteles creatonoti* Viereck (Hymenoptera: Braconidae), *Telenomus* sp. (Hymenoptera: Platygastridae), *Trichogramma* sp. (Hymenoptera: Trichogrammatidae) and C. chlorideae (Hymenoptera: Ichneumonidae) on Corn in India. A year later, [27] and [29] identified four new parasitoids in the same country which are *Odontepyris* sp. (Hymenoptera: Bethylidae); *Eriborus* sp. (Hymenoptera: Ichneumonidae); *Exorista sorbillans* Wiedemann (Diptera: Tachinidae); *Coccygidium melleum* Roman (Hymenoptera: Braconidae) and *C. ruficrus* Haliday (Hymenoptera: Braconidae). The latest research by [24] has identified 5 new parasitoids and one parasite in India. These parasitoids are : *Metopius rufus* Ashmead, *Ichneumon promissorius* Erichson ; *Netelia* sp. (Hymenoptera: Ichneumonidae); *C. formosanus* Sonan; *Microplitis manilae* Ashmead (Hymenoptera: Braconidae). The species Hexamermis cf. albicans Siebold (Mermithida: Mermithidae) remains the only parasite identified during this work in India on Corn. In China, T. remus was the first natural enemy to be identified on Corn in the south of the country [30].

In Africa, although research on possible natural enemies of *S. frugiperda* is recent, to date there are numerous natural enemies, mainly parasitoids, recorded across Africa. The first report on the parasitoid of *S. frugiperda* was done by [25] and later supplemented by [31] and later by the same author [25]. The work of [17]; [18] and [16] completes the very limited list of work done on the natural enemies of this insect in Africa. Indeed, [25] identified for the first time in Africa and more particularly in Tanzania, Ethiopia, Kenya and Mozambique 5 species of eggs and larvae parasitoids of *S. frugiperda* during their work on Corn. They identified for the first time in three localities in Ethiopia *Cotesia icipe* Fernandez, *Coccygidium luteum* Brullé (Hymenoptera: Braconidae) and *Palexorista zonata* (Diptera: Tachinidae). In Kenya, *Charops ater* (Hymenoptera: Ichneumonidae), *P. zonata*, *C.*

luteum, C. icipe and *C. curvimaculatus* were identified in five localities. In Tanzania, however, *C. ater* and *C. luteum* were observed for the first time in four localities. In the Mozambique Republic it was only in 2020 that *C. luteum* and *D. quadrizonula* were reported for the first time on Corn in the central province of Monica. Work on the natural enemies of *S. frugiperda* in West Africa highlighted the presence of *C. bifoveolatus* for the first time in Benin [17], Senegal [18] and Ghana [16]. *C. luteum*, *Charops* sp. and *Meteoridea testacea*, were identified in Benin and Ghana by [16, 17]. *T. remus* has been an important egg parasitoid, identified in South Africa, Benin, Ivory coast, Niger and Kenya by [31] and [25]. Recent studies in Tanzania have identified *C. insularis* as an egg parasitoid of *S. frugiperda* [23].

2) PREDATORS of S. FRUGIPERDA*:* Predators are the second most abundant group after parasitoids and parasites. They represent 19.70% of the species listed in all the articles consulted for this synthesis. These predators belong to five main orders, which are Hymenoptera, Hemiptera, Heteroptera, Coleoptera and Dermaptera.

In the Americas and more specifically in Mexico, [22] reported in their work a single predator species on Corn and Sorghum, a Forficulidae called *Doru* sp. (Dermaptera: Forficulidae). Research in Asia, particularly in India and China, has identified several species of predators. [28], reported the presence of *Forficula* sp (Dermaptera: Forficulidae) in their work. A year later, this species was confirmed in the same country by [29]. The latter were able to record two other species *Harmonia octomaculata* Fabricius and *Coccinella transversalis* Fabricius (Coleoptera: Coccinellidae). The most recent research on the natural enemies of *S. frugiperda* in India was carried out by [24] on Corn. Six (6) species of predator were recorded belonging to three (3) families from three different orders. Hemipterans represented by three (3) species of the Pentatomidae family, two (2) species of Hymenoptera of the family Vespidae and one Heteroptera of the family Reduviidae. These species are *Eocanthecona furcellata* Wolff, *Andrallus spinidens* Fabricius and *Podisus maculiventris* (Hemiptera: Pentatomidae); *Ropalidia brevita* and *Polistes cf*. olivaceus (Hymenoptera: Vespidae) and *Cosmolestes* sp. (Heteroptera: Reduviidae).

3) ENTOMOPATHOGENS of S. FRUGIPERDA : The entomopathogens listed in this inventory are mainly nematodes, fungi, bacteria and viruses. Two (2) species of nematodes were reported in this review. These include *Hexamermis* sp. (Nematoda: Mermithidae), recorded in Senegal on corn (Tendeng et al., 2019) and Ovomermis sinensis (Nematoda: Mermithidae) also on corn in China [32]. Concerning entomopathogenic fungi, *Beauveria bassiana* (Hypocreales: Cordycipitaceae), *Metarhizium anisopliae* (Hypocreales: Clavicipitaceae), *M. rileyi* and *Nomuraea rileyi* (Hypocreales: Clavicipitaceae) were recorded in the different works. *B. bassiana* and *M. anisopliae* were identified in India [19] before being confirmed 3 years later by [33]. In Mexico, the research conducted by [24] reported this species. N. rileyi was the third fungal species reported from India by [28,29]. In Africa, only one species of fungus has been reported in Kenya: *M. rileyi* [34]. Two (2) viruses have been observed in Argentina in Mexico and India and a bacterium in Kenya on Corn as natural enemies of Corn. SfMNPV (Spodoptera frugiperda nucleopolyhedrovirus) was observed in Mexico [37] and India [24; 35] on Corn. On the other hand, SfGV ARG is a virus that has only been observed in Argentina [36]. The bacterium that has been identified in Kenya is Bacterial 16S rRNA gene according to research conducted by [34].

C. SUMMARY OF THE EFFECTIVENESS OF S. FRUGIPERDA NATURAL ENEMIES WORLDWIDE

The management of *S. frugiperda* by means of its natural enemies has been the subject of much research around the world. As well as the inventory of these natural enemies, the implications of parasitoids in the management of this pest are enormous. This section summarises the main work on sustainable management of S. frugiperda during the period 2015-2020.

The majority of publications consulted on the use of natural enemies in the management of S. frugiperda have been carried out in the Americas, where the pest originates. In general, parasitoids and parasites have been the most used. [21] reported a parasitism rate between 5; 6.3 and 9.9% for three main parasitoids on Corn in Mexico which are *C. insularis*, *N. rileyi* and *Trichogramma* spp. In Brazil, [38] reported that the use of *T. pretiosum* in the control of *S. frugiperda* reduced larval density and promoted a production gain of 0.7t/ha equivalent to a financial gain of US$96.5 per hectare. [39] showed that the entomopathogenic virus SfMNPV controlled the population dynamics of S. frugiperda by breaking the insect's resistance. A significant increase in larval mortality of S. frugiperda was obtained in Brazil by [40] using *M. anisopliae* strains. The influence of the migration capacity of *T. remus* on the efficiency of this parasitoid, evaluated in Brazil has been demonstrated [41]. [37] also pointed out that the application of the entomopathogenic virus SfMNPV at a frequency of 7 days controlled the larval density of the caterpillar by 84% and reduced the incidence of parasitoids in Mexico. In the same country, [22] showed the efficiency of T. atopovirilia with parasitism rates of 70, 14 and 8% respectively in laboratory and field conditions. Competition relationships were highlighted by [42] in their work in Brazil on three egg parasitoids *T. remus*, *Trichogramma* spp. and *T. pretiosum* of *S. frigiperda*. [43] showed the effectiveness of the predator-parasitoid symbiosis in controlling the caterpillar in Brazil under laboratory conditions. In Florida, [44] showed the effectiveness of the association of *P. maculiventris*, *E. floridanus* and *C. marginiventris* in the integrated management of *S. frugiperda* and the conditions for a better use of these natural enemies. In their study, [45] showed that the association of the fungus *Trichoderma atroviride* with the Corn root system improved the parasitism rate of *Campoletis sonorensis* (Hymenoptera: Ichneumonidae) on *S. frugiperda* in Mexico. [46] showed the efficacy of *M. anisopliae* in reducing the incidence and level of leaf damage associated with the pest on Corn. Recent investigations in Mexico showed the synergistic effect of combinations of *B. bassiana*, *M. anisopliae* and small doses of spinosad in controlling the dynamics of the L3 stage larvae of *S. frugiperda* in the laboratory [33]. [47] showed the efficiency of *T. remus* in controlling *S. frugiperda* according to the larval density of the parasitoid and the phenological stage of the plant and the influence of temperature in the mass rearing of this parasitoid in Brazil.

In Asia, control trials against S. frugiperda using N. rileyi reduced infestation rates by 58.91-62.87% and leaf damage levels and larval density by 62.50-66.46% and 66.84-73.05% on Corn depending on the locality [48] in India. A parasitism rate between 10 and 15% of this fungus was also reported on Corn one year later in the same country [29]. In their investigations, [49] showed predation of both adults and larvae of *Chrysopa pallens* (Neuroptera: Chrisopidae) on *S. frugiperda*. The entomopathogenic fungus *M. rileyi* and the bacterulovirus, SpfrNPV were reported to be the most dominant entomopathogens in controlling the caterpillar with a larval mortality rate of more than 50 % in India [24].

In Africa, [50] carried out the first work on the efficacy of natural enemies, especially entomopathogenic fungi. They used 20 different concentrations of two strains of fungi, which are B. bassiana and M. anisopliae in the laboratory on L2 stage larvae and neonates in their trials. The lowest efficacy was 30% with B. bassiana on second instar larvae. Most concentrations gave efficacy ranging from 83-97.5% on both second instar larvae and neonates but the best efficiencies were obtained with M. anisopliae. The concentrations that provided the best mortality rates were proposed for experiments under field conditions for further evaluation. [23] showed the efficacy of *C. margiventris* in combination cropping in controlling *S. frugiperda*. In Kenya, *T. remus* was reported to be the most effective egg parasitoid to be promoted in the control of the caterpillar with a parasitism rate of 69.3% against only 42% for the larval parasitoid *C. icipe* [25]. [26] pointed out that with a parasitism rate of 23.68% and 8.86% and relative abundance values of 100 and 96.3 for *C. luteum* and *D. quadrizonula*, respectively, these are important to promote.

III. DISCUSSION

The inventory of the natural enemies of the armyworm through 35 recent articles and publications covering the period 2015-2020, made it possible to identify 67 species belonging to 21 families divided into 10 orders. In general, the work published has focused on three continents: America, Africa and Asia.

Very little work has been done on the inventory of the natural enemies of this caterpillar in America during this period. These results can be explained by the fact that the caterpillar is native to the Americas, and much research has already been carried out in this area with a view to highlighting the biodiversity of the natural enemies of this pest and testing their effectiveness. [51] had already reported for the first time in North and South America, 53 species of parasitoids of *S. frugiperda* belonging to 43 genera and 10 families, of which the families Braconidae, Ichneumonidae and Tachinidae represented respectively 16, 19 and 47 % of the genera and 15, 17 and 53 % of the species. Secondly, [11] identified 150 species of parasitoids and parasits of *S. frugiperda* in the Americas and the Caribbean Basin, belonging to 14 families from 3 main orders: Hymenoptera, Diptera and nematodes. In Africa, as in Asia, many inventories have been made because the caterpillar is a current threat and, as in the country of origin, better control requires a better knowledge of the insect's bioecology. In such a short period of time, the work already done on these continents shows an important biodiversity of natural enemies, including most of those already reported on the American continent. These continents would have many alternative host plants and favourable climatic conditions for the development of the insect and of these natural enemies. These results confirm those of [52] who reported that the insect would be an endemic and multi-generational pest in Africa because the continent offers diverse host plant sources and favourable climatic conditions for constant reproduction.

With regard to the effectiveness of natural enemies, parasitoids were the most effective against the caterpillar. Predators were the second most effective group of natural enemies. These results are in agreement with those of [10] and [20] but disagree with those of [53] who showed that parasitoids, notably *T. remus*, did not have a significant effect on the reduction of *S. frugiperda* larval density and that this reduction was rather linked to natural mortality but also to the action of predators. The natural enemies of *S. frugiperda* would also be those of the main stem and ear borers of Corn, thus explaining the interest in this pest. Indeed, our results confirm those obtained by [54], who showed that *Telenomus busseolae* Gahan and *T. isis* Polaszek were the main ovolarvarian parasitoids of *B. fusca* and *S. calamistis* on Corn, Sorghum and millet. They also confirm those of [55] who reported that *Trichogramma* sp. was the main ovolarvular parasitoid of *Chilo partellus* on Corn and Sorghum. Our results also support those of [56] who mentioned Bracon sesamiae as the main larval parasitoid of *E. saccharina* on Corn. Entomopathogenes have been less recommended because they are slow acting and therefore, in relation to the biology of the insect, would not be effective in controlling it. Our investigations support the work of [33] who recommended a combination of entomopathogenic fungi *B. basssiana* and *M. anisopleae* with small doses of spinosad insecticides to control L3 stage larvae in the laboratory. They also support those of [57] with the use of the entomopathogenic nematode *Steinernema carpocapsae* (Rhabditida: Steinernematidae) in combination with low doses of chemical pesticides in the management of *S. frugiperda* in the USA. In Africa, [25; 58] were able to promote the first natural enemies to be valued. *T. remus* was proposed by [17] in Ghana and Benin and [16] in Ghana to control the caterpillar.

According to [59], the production of a parasitoid such as *T. remus* on *S. frugiperda* eggs would require 0.0004 US$ (on average 3 CFA francs). Given the whole process to be followed before their release, the production cost of natural enemies would remain one of the major constraints to biological control based on the use of natural enemies in Africa.

IV. CONCLUSION

At the end of this study, it is noted that there is a significant diversity of natural enemies of S. frugiperda around the world. Very little research has been done on natural enemy inventories in the USA, unlike in other countries. This is because much work has already been done to identify natural enemies, and perspectives on their efficacy are sought. In contrast, in African and Asian countries, research on potential natural enemies is just beginning. In only five years after its official report on the African continent and only two years on the Asian continent, the majority of the natural enemies listed on the American continent have already been found on these continents. This study lays the groundwork for the start of research into the use of the most effective natural enemies in our countries. The research is ongoing and will allow a better assessment of natural enemies and their efficacy in Africa.

ACKNOWLEDGEMENTS

The authors thank the maize producers for their courage and commitment to the control of the armyworm. They also thank the entire scientific community for their efforts.

REFERENCES

1) Adam, S., Edorh, P. A., Totin, H., Koumoulou, L., Amoussou E., Aklikokou, K. and Boko, M. 2010. Pesticides et métaux lourds dans l'eau de boisson, les sols et les sédiments de la ceinture cotonnière de Gogounou, Kandi et Banikoara (Benin). *International Journal of Biological and Chemical Sciences*, 4: 1170-1179.
2) Alain, K., Sawadogo, W., Nianogo J., Millogo-Rasolodimby, J., 2009. Usage des intrants chimiques dans un agrosystème tropical: diagnostic du risque de pollution environnementale dans la région cotonnière de l'est du Burkina Faso, Biotechnologie, Agronomie, Société et Environement, 4: 499-507.
3) Kostandini, G. and La Rovere R. 2015. Ex-ante welfareanalysis of technological change: the case of nitrogen efficient maize for African soils. *Canadian Journal of Agriculture Economics,* 64: 147-168.
4) Day, R., Abrahams, P., Bateman, M., Beale, T., Clotte, V., Cock M., Colmenarez, Y., Corniani, N., Early, R., Godwin, J. and *al.* 2017. Fall armyworm: impacts and implications for Africa. *Outlooks on Pest Management*, 28:196-201.
5) FAO. 2016. Guidelines on Highly Hazardous Pesticides. International Code of Conduct on Pesticide Management. Rome, Italy.
6) Wilmar, R-C., Julio C. R., Leopolodo C-L., Alfredo, C. and Edi A. M. 2016. Attraction, Feeding Preference, and Performance of *Spodoptera frugiperda* Larvae (Lepidoptera: Noctuidae) Reared on Two Varieties of Maize. *Environmental Entomology,* 45: 384-389. doi:10.1093/ee/nvv229.
7) Riggin, T. M., Espelie K. E., Wiseman, B. R. and Isenhour D. J. 1993. Distribution of fall armyworm (Lepidoptera: Noctuidae) parasitoids on five corn genotypes in South Georgia. *Florida Entomologist*, 76: 292–302.
8) Rios-Velasco, C., Gallegos-Morales, G., Cambero-Campos, J., Cerna-Chávez, E., Del Rincón-Castro, M. C. and Valenzuela-García R. 2011. Natural enemies of the fall armyworm Spodoptera frugiperda (Lepidoptera: Noctuidae) in Coahuila, México. *Florida Entomologist,* 94: 723–726.
9) Hogg, D. B., Anderson, R. E. and Pitre H. N. 1982. Early-season parasitization of fall armyworm (Lepidoptera: Noctuidae) larvae in Mississippi. *Florida Entomologist*, 65: 584–585.
10) Meagher, R. L., Nuessly, G., Nagoshi, R. N. and Hay-Roe, M. M. 2016. Parasitoids attacking fall armyworm (Lepidoptera: Noctuidae) in sweet corn habitats. *Biological Control*, 95: 66–72.
11) Molina-Ochoa, J. Carpenter J. E., Heinrichs E. A. and Foster J. E. 2003. Parasitoids and parasites of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in the Americas and Caribbean Basin: an inventory. *Florida Entomologist*, 86 254-289.

12) Beserra, E. B., Dias, C. T. and Parra, J. R. P. 2002. Distribution and natural parasitism of Spodoptera frugiperda (Lepidoptera: Noctuidae) eggs at different phenological stages of corn. *Florida Entomologist*, 85: 588–593.
13) Murúa, M. G., Molina-Ochoa, J. and Fidalgo, P. 2009. Natural distribution of parasitoids of larvae of the fall armyworm, Spodoptera frugiperda, in Argentina. *Journal of Insect Science,* 9: 20. doi: 10.1673/031.009.2001.
14) Nagoshi, R. N., Koffi D., Agboka K., Tounou K. A., Banerjee R., Jurat-Fuentes J. L et Meagher R. L., 2017. Comparative molecular analyses of invasive fall armyworm in Togo reveal strong similarities to populations from the eastern United States and the Greater Antilles. *PLoS ONE*, 12: 1-15. https://doi.org/10.1371/journal.pone.0181982.
15) Meagher, Jr. L. R., Agboka, K., Tounou, K. A., Koffi, D., Agbevohia, A. K., Amouze, R. T., Adjevi, M. K. and Nagoshi N. R. 2019. Comparison of pheromone trap design and lures for Spodoptera frugiperda in Togo and genetic characterization of moths caught. The Netherlands Entomological Society Entomologia Experimentalis et Applicata 1–10.
16) Koffi, D., Kyerematen R., Eziah V. Y., Agboka K. et Adom M. *et al.,* 2020. Natural Enemies of the Fall Armyworm, Spodoptera frugiperda (J.E. Smith) (Lepidoptera: Noctuidae) in Ghana. *Florida Entomologist*, 103: 85-90.
17) Agboyi, L. K., Goergen G., Beseh P., Mensah S. A., Clottey V. A., Glikpo R., Buddie A., Cafà G., Oord L., Day R. , Ivan R. and Kenis M. 2019. Parasitoid Complex of Fall Armyworm, *Spodoptera frugiperda*, in Ghana and Benin. *Insects*, 10. doi:10.3390/insects10110410.
18) Tendeng, E., Labou, B., Diatte, M., Djiba S. and Diarra, K. 2019. The fall armyworm Spodoptera frugiperda (J. E. Smith), a new pest of maize in Africa: Biology and first native natural enemies detected. *International Journal of Biological and Chemistry Sciences*, 13: 1011–1026.
19) Ordóñez-García, M., Rios-Velasco C., Berlanga-Reyes D. I., Acosta-Muñiz C. H., Salas-Marina M. A. and Cambero-Campos, O. J. 2015. Occurrence of natural enemies of Spodoptera frugiperda (Lepidoptera: Noctuidae) in Chihuahua, Mexico. *Florida Entomologist*, 98: 843–847.
20) López, M. A., Martínez-Castillo A. M., García-Gutiérrez C., Cortez-Mondaca E. and EscobedoBonilla C. M. 2018. Parasitoids and Entomopathogens Associated with Fall Armyworm, *Spodoptera frugiperda*, in Northern Sinaloa. *Southwestern Entomologist*, 43: 867-881.
21) Araiza, M. D. S. 2018. Natural Enemies of the Fall Armyworm1 and the Corn Earworm2 in Sorghum and Maize in Irapuato, Guanajuato, Mexico. *Southwestern Entomologist*, 43:715-722.
22) Jaraleño-Teniente, J., Lomeli-Flores J. R., Rodríguez-Leyva E., Bujanos-Muñiz R. and Rodríguez-Rodríguez E. S. 2020. Egg Parasitoids Survey of Spodoptera frugiperda (Smith) (Lepidoptera: Noctuidae) in Maize and Sorghum in Central Mexico. *Insects*, 11, 157. doi:10.3390/insects11030157.
23) Ngangambe, M. H. et Mwatawala W. M. 2020. Effects of entomopathogenic fungi (EPFs) and cropping systems on parasitoids of fall armyworm (Spodoptera frugiperda) on maize in eastern central, Tanzania. *Biocontrol Science and Technology*, DOI: 10.1080/09583157.2020.1726878.
24) Firake, D.M. and Behere G. T. 2020. Natural mortality of invasive fall armyworm, Spodoptera frugiperda (J. E. Smith) (Lepidoptera: Noctuidae) in maize agroecosystems of northeast India. *Biological Control*, 148. doi:10.1016/j.biocontrol.2020.104303.
25) Sisay, B., Simiyu J., Malusi P., Likhayo P., Mendesil E., Elibariki N., Wakgari M., Ayalew G. and Tefera T. 2018. First report of the fall armyworm, *Spodoptera frugiperda* (Lepidoptera: Noctuidae), natural enemies from Africa. *Journal of Applied Entomology*, 142: 800-804.
26) Caniço, A., Mexia, A. and Santos L. 2020. First Report of Native Parasitoids of Fall Armyworm Spodoptera frugiperda Smith (Lepidoptera: Noctuidae) in Mozambique. *Insects*, 11: 1-12. Doi:10.3390/insects11090615.
27) Ankita, G., Ramesh, B. S. and Kumar, M. S. 2019. *Cotesia ruficrus* (Haliday, 1834) (Hymenoptera: Braconidae) emerging as a common natural parasitoid of Spodoptera frugiperda (J. E. Smith) (Lepidoptera: Noctuidae) in Indian maize fields. *Journal of Biological Control*, 33: 193-196.
28) Shylesha, A. N., Jalali, S. K., Gupta, A., Varshney, R., Venkatesan, T., Shetty, P., Ojha, R., Ganiger, P. C., Navik, O., Subaharan, K., Bakthavatsalam, N. and Ballal, C. R. 2018. Studies on new invasive pest *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae) and its natural enemies. *Journal of Biological Control*, 32: 145-151.
29) Sharanabasappa, Kalleshwaraswamy, C. M., Maruthi, M. S., Pavithra, H. B., Poorani, J. and Diraviam, J., 2019. Natural enemies of Spodoptera frugiperda (J. E. Smith) (Lepidoptera: Noctuidae), a recent invasive pest on maize in South India. *Florida Entomologist,* 102: 618-623. doi:10.1653/024.102.0335.

30) Liao, Y., Yang, B., Xu, M., Lin, W., Wang, D., Chen, K. and Chen, H. 2019. First report of *Telenomus remus* parasitizing *Spodoptera frugiperda* and its natural parasitism in South China. Article in press.
31) Kenis, M., du Plessis, H., Van den Berg, J., Ba, M., Goergen, G., Kwadjo, K., Baoua, I., Tefera, T., Buddie, A., Cafà, G., Offord, L., Rwomushana, I. and Polaszek, A. 2019. *Telenomus remus*, a Candidate Parasitoid for the Biological Control of Spodoptera frugiperda in Africa, is already Present on the Continent. Insects 10, 92. doi:10.3390/insects10040092.
32) Sun, B., Li, F., He, X., Cao, F., Bandason, E., Shapiro-Ilan, D., Ruan, W. and Wu, S. 2020. First report of *Ovomermis sinensis* (Nematoda: Mermithidae) parasitizing fall armyworm *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in China. *Journal of nematology*, 52. e2020-50.
33) Rivero-Borja, M., Guzmán-Franco, A. W., Rodríguez-Leyva, E., Santillán-Ortega, C. and Pérez, P. A. 2018. Interaction of Beauveria bassiana and Metarhizium anisopliae with chlorpyrifos ethyl and spinosad in Spodoptera frugiperda larvae: Fungusinsecticide interactions. *Pest Management Science*, 74 : 2047-2052.
34) Gichuhi, J., Subramanian, S., Khamis, F. M., Van den Berg, J., du Plessis, H., Ekesi, S. and Herren, J. K. 2019. Diversity of fall armyworm, *Spodoptera frugiperda* and their gut bacterial community in Kenya. doi: https://doi.org/10.1101/664987.
35) Raghunandan, B. L., Patel, N. M., Dave, H. J. and Mehta, D. M. 2019. Natural occurrence of nucleopolyhedrovirus infecting fall armyworm, *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae) in Gujarat, India. *Journal of Entomology and Zoology Studies,* 7: 1040-1043.
36) Luis Pidre, M., Sabalette, K. B., Romanowski, V. and Ferrelli, M. L. 2018. Identification of an Argentinaan isolate of Spodoptera frugiperda granulovirus*. Revista A rgentina de Microbiología,* 51:381-385.
37) García-Banderas, D., Tamayo-Mejía, F., Pineda, S., de la Rosa, J. I. F., Lasa, R., Chavarrieta-Yá ñez, J. M., Gervasio-Rosas, E., Zamora-Avilés, N., Morales, S. I., Ramos-Ortiz, S.,Valle, J. and Martínez-Castillo, A. M. 2020. Biological characterization of two Spodoptera frugiperda nucleopolyhedrovirus isolates from Mexico and evaluation of one isolate in a small-scale field trial. *Biological Control*, 104316. https://doi.org/10.1016/j.biocontrol.2020.104316.
38) Figueiredo, M. L. C., Cruz, I., da Silva, R. B. and Foster, J. E. 2018. Biological control with *Trichogramma pretiosum* increases organic maize productivity by 19.4%. *Agronomy for Sustainable Development,* 35:1175–1183.
39) Bentivenha, J. P. F., Rodrigues, J. G., Lima, M. F., Marçon, P., Popham, H. J. R. and Omoto, C. 2018. Baseline Susceptibility of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) to SfMNPV and Evaluation of Cross-Resistance to Major Insecticides and Bt Proteins. *Journal of Economic Entomology*, 20: 1–8.
40) de Lira, A. C., Mascarin, G. M. and Delalibera, J. Í. 2020. Microsclerotia production of *Metarhizium* spp. for dual role as plant biostimulant and control of *Spodoptera frugiperda* through corn seed coating, *Fungal Biology*, doi: https://doi.org/10.1016/j.funbio.2020.03.011.
41) Pomari-Fernandes, A., Bueno, A. F., De Bortoli, S. A. and Favetti, B. F. 2018. Dispersal capacity of the egg parasitoid *Telenomus remus* Nixon (Hymenoptera: Platygastridae) in maize and soybean crops. *Biological Control*, 126: 158–168.
42) Dasilva, C. S. B., Vieira, J. M., Loiácono, M., Margaría, C. and Parra, J. R. P. 2015. Evidence of exploitative competition among egg parasitoids of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in maize. *Revista Colombiana de Entomología*, 41: 184-186.
43) Moral, R. A., Demétrioa, C. G. B. HIndia, J. B., Godoy, A. W. C. and Fernandes, F. S. 2016. Parasitism-mediated prey selectivity in laboratory conditions and implications for biological control, Basic and Applied Ecology, article in press.
44) Perier, J. D. 2018. Integration of two predaceous stinbugs and a larval parasitoid to manage the Fall armyworm *Spodoptera frugiperda* (Lepidoptera: Noctuidae). College of agricultural and food sciences in partial fulfillment of the requirement of the degree of Master in science in agricultural sciences, 66p.
45) Contreras-Cornejoa, H. A., del-Vala, E., Macías-Rodríguezc, L., Alarcónd, A., Carlos, E. González-Esquivela, C. E. and Larsena, J. 2018. *Trichoderma atroviride*, a maize root associated fungus, increases the parasitism rate of the fall armyworm *Spodoptera frugiperda* by its natural enemy Campoletis sonorensis. *Soil Biology and Biochemistry*, 122:196–202.
46) Hernandez-Trejo, A., Estrada-Drouaillet, B., López-Santillán, J. A., Rios-Velasco, C., Rodríguez-Herrera, R. and Osorio-Hernández, E. 2019. Effects of Native Entomopathogenic Fungal Strains and Neem Extract on *Spodoptera frugiperda* on Maize. *Southwestern Entomologist*, 44: 117-124.

47) Salazar-Mendoza, P., Rodriguez-Saona, C. and Fernandes, A. O. 2020. Release density, dispersal capacity, and optimal rearing conditions for *Telenomus remus*, an egg parasitoid of *Spodoptera frugiperda*, in maize. *Biocontrol Science and Technology*, DOI: 10.1080/09583157.2020.1776841.
48) Mallapur, C., Naik, A. K., Hagari, S. and Lingappa, S. 2018. Potentiality of Nomuraea rileyi (Farlow) Samson against the fall armyworm, Spodoptera frugiperda (J.E Smith) infesting maize. *Journal of Entomology and Zoology Studies,* 6.
49) Qing Xuan, X., Song, W., RenBin, T., Su, W., Fan, Z., Jiao, M., Shu, L. and Ning D. 2019. Study on the predation potential of *Chrysopa pallens* on *Spodoptera frugiperda*. *Journal of Environmental Entomology*, 41: 754-759.
50) Akutse, K. S., Kimemia, J. W., Ekesi, S., Khamis, F. M., Ombura, O. L. and Subramanian, S. 2019. Ovicidal effects of entomopathogenic fungal isolates on the invasive Fall armyworm *Spodoptera frugiperda* (Lepidoptera: Noctuidae). *Journal of Applied Entomology*, 00: 1-9. https://doi.org/10.1111/jen.12634.
51) Ashley, T. R. 1979. Classification and distribution of fall armyworm parasites. *Florida Entomologist*, 62: 114–123.
52) Goergen, G., Kumar, P., Sankung, S., Togola, A. and Tamò, M. 2016. First Report of Outbreaks of the Fall Armyworm Spodoptera Frugiperda (J E Smith) (Lepidoptera, Noctuidae), a New Alien Invasive Pest in West and Central Africa*, PLoS ONE*, 10: e0165632.
53) Varella, A. C., Menezes-Netto, C. A., Alonso, J. D., Caixeta, D. F., Peterson, R. K. D. and Fernandes, O. A. 2015. Mortality Dynamics of Spodoptera frugiperda (Lepidoptera: Noctuidae) Immatures in Maize. *PLoS ONE,* 10. doi:10.1371/journal.pone.0130437.
54) Polaszek, A. 1992. Cereal stem boers and their parasitoids in Africa. *Proceedings of the Section Experimental and Applied Entomology of the Netherlands Entomological Society,* 3:70-71.
55) Skovgård, H. and Päts P., 1996. Effects of intercropping on maize stemborers and their natural enemies. *Bulletin of Entomological Research*, 86: 599-607. doi:10.1017/s0007485300039407.
56) Polaszek, A. 1995. Cereal stem borers in Africa: Taxonomy and natural enemies. Handbook for training course held at ICIPE Nairobi, 15–28 October 1995.
57) Viteri, D. M., Linares, A. M. and Flores, L. 2018. Use of the entomopathogenic nematode Steinernema carpocapsae in combination with low-toxicity insecticides to control fall armyworm (Lepidoptera: Noctuidae) larvae. *Florida Entomologist,* 101:327–9.
58) FAO, 2018b**.** Gestion intégrée de la chenille légionnaire d'automne sur le maïs. Un guide pour les champs-écoles des producteurs en Afrique. Pesticides botaniques pour la gestion de la chenille légionnaire d'automne.
59) Vieira, N. F., Pomari-Fernandes, A., Lemes, A. A. F., Vacari, A. M, De Bortoli, S. A. and Bueno, A. F. 2017. Cost of Production of *Telenomus remus* (Hymenoptera: Platygastridae) Grown in Natural and Alternative Hosts. *Journal of Economic Entomology,* 110: 2724–2726.