Review Article

BIOLOGICAL CONTROL OF *Spodoptera frugiperda* (J.E SMITH) (LEPIDOPTERA: NOCTUIDAE) GLOBALLY AND NEWLY NATURAL ENEMY ASSOCIATIONS IN ASIAN COUNTRIES: A REVIEW

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ABSTRACT

Spodoptera frugiperda (J.E Smith) is a destructive pest of maize (*Zea mays* L.) around the globe. It originated from the American continent and subsequently invaded Africa and Asia. Despite its recent invasion into Asia, some countries such as India, China, Pakistan, the Philippines, Indonesia, Sri Lanka, Malaysia, and Nepal have already reported numerous bio-control agents of *S. frugiperda*. In Asia, several bio-control agents of *S. frugiperda* are frequently encountered, including the egg parasitoid, *Telenomus remus* (Nixon) and the egg-larval parasitoid, *Chelonus formosanus* (Sonan). The Hymenopteran family Braconidae was the presiding larval parasitoid group, while the dominant predatory groups belong to family Reduviidae, Coccinellidae, and Pentatomidae. *T. remus* is considered the most effective and extensively used bio-control agent of *S. frugiperda*. Therefore, we discuss the potential of the bio-control agents and successful efforts in the biological control programme globally, along with new natural enemy associations with recently invaded *S. frugiperda* in Asian countries. This review may encourage other Asian nations with *S. frugiperda* problem to adopt natural enemies-based sustainable and environmentally friendly approaches.

Key words: Asia, bio-control, natural enemies, parasitoids, predators, *Spodoptera frugiperda*

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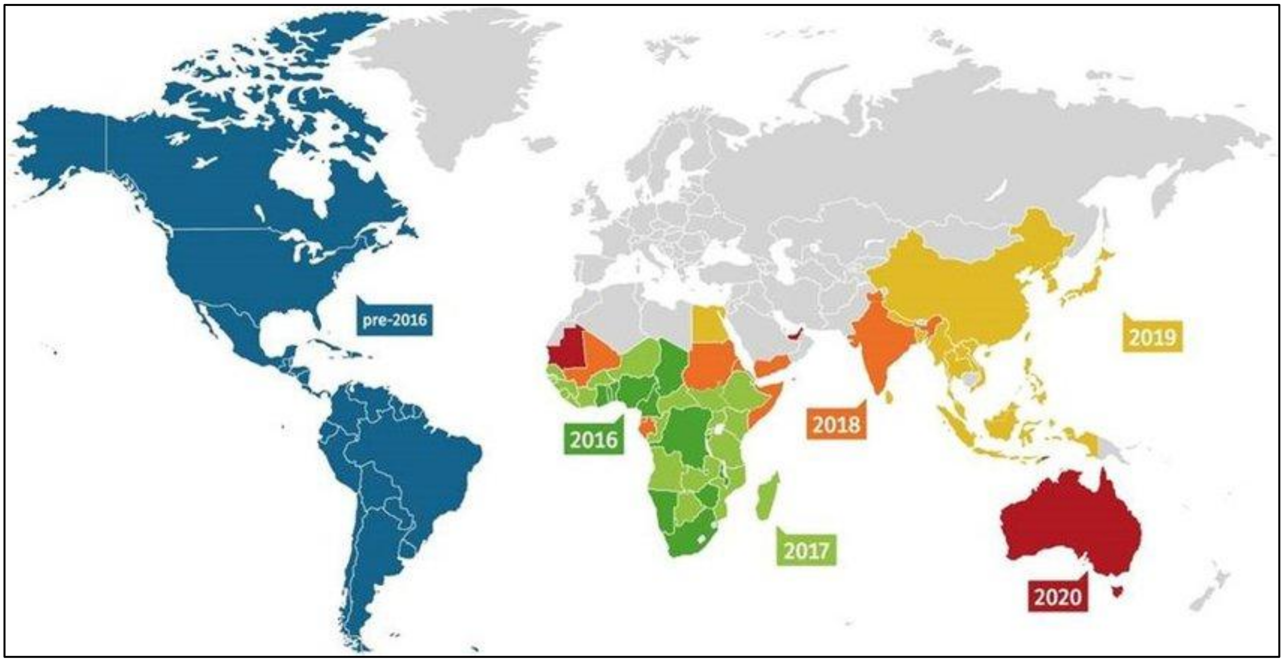
INTRODUCTION

The Fall armyworm (FAW) or *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae), is an extremely destructive agricultural pest indigenous to the Americas (Goergen *et al*., 2016). It possesses the capacity to fly over many kilometres, rapid breeding, and attack 353 host species consisting of numerous plant families, about 76 (Adhikari *et al*., 2020). Therefore, it is regarded as one of the agile, highly polyphagous, and destructive noctuid moths in the agricultural fields (Nagoshi and Meagher, 2008). Globally, this pest significantly reduces crop yields, *Zea mays* L. being the most susceptible plant in the Poaceae family (Rwomushana *et al*., 2018). Other than the Poaceae family, Amaranthaceae, Brassicaceae, Amaryllidaceae, Fabaceae, Malvaceae, and Solanaceae plant families are also vulnerable to *S. frugiperda* attack (Lu and Adang, 1996).

Farmers tend to apply insecticides considering the damage severity of the global crop production caused by insect attacks (Abang *et al*., 2021). Though it is a recommended practice under integrated pest management (IPM), it is not a long-term solution or nature-friendly remedy. Despite it is easy control method, its overuse might cause an undesirable negative impact on nature (Kumar *et al*., 2022). Continuous application of insecticides over many years can cause the development of resistance and pose a substantial threat to beneficial insects and biodiversity (Yu *et al*., 2003). More than 29 insecticide active ingredients belonging to six modes of action groups have been ineffective due to the resistance developed by *S. frugiperda* (Wu *et al*., 2019), which include some extensively used insecticide categories such as carbamates, organophosphates, and pyrethroids (Yu, 1991). Moreover, *S. frugiperda* can develop resistance against transgenic maize plants expressing Cry1A.105 (MON89034), and the Cry1F gene expressing (TC1507) genetically modified maize varieties (Farias *et al*., 2014; Bernardi *et al*., 2017). Furthermore, in the Americas, *S. frugiperda* can also develop resistance against *Bacillus thuringiensis* (Bt) proteins (Hung, 2021). These challenges accelerate attempts to find sustainable and eco-friendly options to control *S. frugiperda*. Bio- control is one of the sustainable, eco-friendly, efficient, economical, and safe solutions in crop protection (Assefa and Ayalew, 2019). Therefore, identification of natural enemies is crucial to implement the bio-control management of *S. frugiperda* (Chhetri and Acharya, 2019; Lamsal *et al*., 2020).

Native natural enemies play a major roll to defending against the invasive pest species (Firake and Behere, 2020). Therefore, searching for native natural enemies against invasive *S. frugiperda* is crucial, and it is one of the initial steps of the pest management involving bio- control. Numerous bio-control agents of *S. frugiperda* have been found by Asian nations despite it recently invading Asia. Therefore, available literature on the bio-control agents of *S. frugiperda* in some countries of Asia is gathered in this review, along with the evidence of some successful attempts and their potential for the bio-control programme in some countries. For this purpose the scientific evidence from research papers published on the bio-control agents of *S. frugiperda* was carefully examined using various online databases, including Google Scholar, WoS, Scopus, PubMed, and ScienceDirect. All search terms included "fall armyworm," or "FAW," or "*Spodoptera frugiperda*," combined with following keywords: "natural enemies," "Asia," "predators," "parasitoids," "pathogens," "entomopathogens," "parasitism," and "biological control." Based on the relevance to the review paper, articles were selected. Ultimately, 130 of the most pertinent research papers were thoroughly reviewed to compile the content of the review paper. Additionally, the associations of natural enemies in Asian countries were also tabulated scientifically.

The dissemination of *S. frugiperda* in the Asian continent after America and Africa: *S. frugiperda* originated in America. Subsequently, in late 2016, it invaded the African continent (Cock *et al*., 2017). Afterward, it was dispersed to Asia in 2018 (Mahat *et al*., 2021). *S. frugiperda* was reported in South Asia in 2018, with reports from India (Sharanabasappa *et al*., 2018), subsequently reported in Sri Lanka (Perera *et al*., 2019), and Bangladesh (Alam *et al*., 2018). It was reported in Nepal (Guragain, 2019), Bhutan (Mahat *et al*., 2021), and Pakistan (Gilal *et al*., 2020) in 2019. Afterward, it invaded from South Asia to Southeast Asia rapidly (Lamsal *et al*., 2020). Consequently, it reported Myanmar and Thailand in 2018 as the first time in this region (IPPC, 2021). Subsequently, it was reported in Indonesia (Sartiami *et al*., 2020), Malaysia (Jamil *et al*., 2021), Vietnam (FAO, 2019d), the Philippines, and Laos (IPPC, 2021). It has been reported in East Timor, Cambodia, and Brunei by 2021 (IPPC, 2021). It was first reported in China as the first country in the East Asian region in 2018, and by 2019, it had spread to Japan and South Korea (IPPC, 2021).



(Source : FAO, 2020)

Figure 1. The global dispersal of *S. frugiperda*.

Opportunities for the bio-control of *S. frugiperda:* Bio-control refers to the beneficial impact of the predators, competitors, parasitoids, and pathogens in controlling pest populations (Nafiu *et al*., 2014). Natural enemies act as the bio-control agents in the biological control programme as a sustainable and cost-effective tool instead of synthetic chemicals (Ogunfunmilayo *et al*., 2021). Limited usage of pesticides by the farmers is a direct impact of the biological control, it enhances the food quality and food security, and ultimately it benefit to human health (Van Lenteren, 2012). Cock *et al*. (2010) specified that the biological control positively links with the ecosystem services, biodiversity conservation, and invasive species management. However, to succeed in a bio-control pest management plan, identification of bio-control agents is vital (Bonsignore and Vacante, 2012a).The bio-control potential can be assessed from the global identification of their natural enemies. For instance, more than 150 parasitoid species associated with *S. frugiperda* have been reported in the Caribbean and the Americas (Molina-Ochoa *et al*., 2003a). The majority belongs to the orders Hymenoptera and Diptera, with Ichneumonidae and Braconidae being the widely distributed families within Hymenoptera, while Tachinidae was the widely distributed family in Diptera (Molina-Ochoa *et al*., 2003). About 30 native parasitoid species targeting *S. frugiperda* have already been discovered in 17 African countries (Sisay *et al*., 2019b). Additionally, numerous parasitoid species have been identified predominantly in India and China, associated with *S. frugiperda* (Shylesha *et al*., 2018; Sharanabasappa *et al*., 2019; Yang *et al*., 2022).

Parasitoids exhibit a higher degree of specificity and are closely linked to one of the pest stages (Gowda *et al*., 2021). Egg parasitoids can control the pest before crop damage occurs. Therefore, they are recognized as the unique natural enemies for controlling agricultural pest species. During the parasitization process, they specifically search for the egg stage and attack at that stage. Consequently, they can break the further development and destroy the pest at the egg stage. Therefore, they are recognized as the efficient bio-control agents for the mass-reared and released strategy in a sustainable pest management approach (Parra and Coelho Jr. 2019). The genus *Telenomus* and *Trichogramma* are two of the prevalent egg parasitoid genera, including many egg parasitoid species that can parasitized the eggs of *S. frugiperda* successfully (Zang *et al*., 2021). Therefore, they are recognized as the ideal option for targeting *S. frugiperda* eggs in the biological pest management programme (Agboyi *et al*., 2020). *Telenomus remus* (Nixon) is one of the efficient egg parasitoid species due to its high fecundity and its unique parasitism ability, because it can reach the bottom layers of the *S. frugiperda* egg mass and parasitize the whole egg mass (Bueno *et al*., 2008). In contrast, *Trichogramma* species are partially effective because they cannot reach inside layers of *S. frugiperda* egg mass and are unable to parasitize the whole egg mass (Laminou *et al*., 2020). Other than egg parasitoids, an egg- larval parasitoid, *Chelonus insularis* (Cresson), is a frequently reported parasitoid species in the native range (Bahena and Cortez, 2015). Larval parasitoids, namely *Campoletis sonorensis* (Cameron), *Campoletis flavicincta* (Ashmead), and *Pristomerus spinator* (Fabricius) also abundantly recorded in the native range (Molina-Ochoa *et al*., 2003). In the African continent, the most prevalent larval parasitoids of *S. frugiperda* belong to the ichneumonid *Charops* sp., braconids *Chelonus bifoveolatus* (Szepligeti), *C. curvi-maculatus* (Cameron), *Cotesia icipe* (Fernandez-Triana and Fiaboe), and tachinids *Drino quadrinozula* (Thomson) (Amadou *et al*., 2018; Agboyi *et al*., 2020; Abang *et al*., 2021; Otim *et al*., 2021).

Not only parasitoids but also many predator species significantly contribute to managing *S. frugiperda* (Firake and Behere, 2020a). Some of them have been successfully employed under the augmentative release approach to efficiently control the pest populations (Collier and Van Steenwyk, 2004). Predators are capable of targeting multiple developmental stages of fall armyworm (Abbas *et al*., 2022), and different taxa specialize in attacking distinct life stages (Harrison *et al*., 2019). Varella *et al*. (2015) who mentioned that the eggs and larvae of *S. frugiperda* are more vulnerable to predation by different predator species than to parasitoid attack. Bahena and Cortez (2015) documented sixty five predator species of *S. frugiperda*, primarily associated with the egg and larval stages. Several insect predators belonging to Dermaptera, Coleoptera, Hymenoptera, and Hemiptera have been effectively utilized in augmentative biological control programmes across the Americas (Abbas *et al*., 2022). Commonly reported predators include *Orius tristicolor* (White) and *O. insidiosus* (Say) (Hemiptera: Anthocoridae), *Harmonia axyridis* (Pallas) (Coleoptera: Coccinellidae), *Sinea confusa* (Caudell) (Hemiptera: Reduviidae), *Doru lineare* (Eschscholtz), and *D. luteipes* (Scudder) (Dermaptera: Forficulidae) (Bahena and Cortez, 2015; Varella *et al*., 2015). *S. frugiperda* larvae are also preyed on by certain social and solitary wasp species (Sousa *et al*., 2011; Southon *et al*., 2019). In India, twelve predator species were reported by Firake and Behere (2020a), including tiger beetles (Coleoptera: Cicindelidae), paper wasps (Hymenoptera: Vespidae), and earwigs (Dermaptera: Forficulidae), with the pentatomid bug *Eocanthecona furcellata* (Wolf) identified as the most dominant predator. Beyond insect predators, nematodes (Sun *et al*., 2020), various spider species (Anandhi and Saminathan, 2021), bacteria (Sivakumar *et al*., 2020), fungi (Manjula *et al*., 2019), and viruses (Raghunandan *et al*., 2019) also act as an integral part of the bio- control agents of *S. frugiperda*.

Successful evidence for bio-control implementation against *S. frugiperda* in the field: In the American continent, numerous bio-control agents, such as predators, pathogens, and parasitoids of *S. frugiperda* have been documented (Molina-Ochoa *et al*., 2003). In African countries, they have also reported a wide range of bio-control agents after the invasion of *S. frugiperda* (Sisay *et al*., 2019). Though it has recently invaded Asia, some Asian countries reported many natural enemies of *S. frugiperda* within this time duration (Firake and Behere, 2020). According to Ahissou *et al*. (2021), *S. frugiperda* mortality on its native continent can reach 42% due to natural enemies, which significantly contributes to maintain the natural equilibrium of the pest population. Firake and Behere (2020a) reported that natural enemies in maize fields in northeastern India cause between 57 and 73% of *S. frugiperda* larval mortality. Unsprayed fields in America exhibit more than 44% of natural parasitism against *S. frugiperda* (FAO, 2017).

Telenomus remus was first introduced into the Americas through field releases in Barbados during 1971–1972, achieving parasitism rates of over 60% (Cave, 2000). Subsequent augmentative releases in Latin America and Venezuela have resulted in up to higher egg parasitism about 90% (Cave, 2000; Ferrer *et al*., 2001). Field evaluations further revealed parasitism levels of 80–100% in Venezuela and Ghana, providing effective suppression of *S. frugiperda* populations (Cave, 2000; Pomari *et al*., 2012). Native parasitoids from Sub-Saharan African countries exhibit higher levels of parasitism (Assefa and Ayalew, 2019). In Niger, experimental releases of *T. remus* alongside a *Trichogrammatoidea* sp. in sorghum fields achieved 64% parasitism in the initial field experiments (Laminou *et al*., 2020). Abang *et al*. (2021) reported that natural parasitism of egg parasitoids (*T. remus* and *T. chilonis*) ranged from 50 to 100% across various agro-ecological zones in Cameroon. Furthermore, *T. remus* demonstrated parasitism of eggs exceeding 50% in Tanzania and Kenya (Sisay *et al*., 2019). Sadore in Niger, the augmentative release of *T. remus* led to a 64% parasitism (Laminou *et al*., 2020), and between 60% and 90% in Latin America (Cave, 2000). According to Agboyi *et al*. 2021, field parasitism of *T. remus* was observed at 30 to 100% in Ghana.

In Karnataka, India, egg parasitism of *S. frugiperda* by *Trichogramma chilonis* (Ishii) was 24%, and by *T. remus* was 9% (Navik *et al*., 2021). When *S. frugiperda* first invaded in 2018, parasitism by *T. chilonis* ranged between 1.08 to 1.20% respectively. However, in 2019-2020, parasitism level increased significantly, ranging from 2.28 to 20% across various regions in Karnataka, India. *T. chilonis* parasitism rates varied from 7.5 to 18% in Maharashta. *T. remus* parasitism in Karnataka was between 1.0% and 7% in 2018, and 1.2 to 8% in 2019-20 (ICAR-NBAIR, 2020). Hainan province in China, *T. remus* parasitized 28.9% of egg masses (Tang *et al*., 2020a), and in Guangdong province it was 30.6% (Huo *et al*., 2019). In southeastern China, field application of *T. remus* to control FAW resulted in 100% parasitism for egg masses and 84% for individual eggs (Zhao *et al*., 2020). In maize fields of Shandong Province, China, studies on *T. chilonis* recorded 73% egg mass parasitism and 86% for individual eggs (Yang *et al*., 2019).

Other than egg parasitoids, larval parasitoids also contribute to considerably higher parasitism levels in the field. For instance, larval parasitism of *S. frugiperda* in the pesticide free fields in the southern USA has reached up to 44% (Meagher *et al*., 2016). In Costa Rica and Nicaragua, reported more than 60% larval parasitism of *S. frugiperda* (Marenco and Sauders, 1993). In Ethiopia, *Cotesia icipe* (Hymenoptera: Braconidae) has shown 33.8 to 45.3% larval parasitism, being a predominant larval parasitoid in Ethiopia (Sisay *et al*., 2018). In Kenya, the most prevalent Tachinid fly, *Palexorista zonta* exhibit parasitism rate of 12.5%, in Tanzania and Kenya, *Charops ater* and *Coccygidium luteum* parasitism rates are reported to be 4.0 to 8.3% and 6.0 to 12%, respectively (Sisay *et al*., 2018). Agboyi *et al*. (2021) stated that larval parasitoids severely attack young larvae of *S. frugiperda* in Ghana. Moreover, more than 20% of *S. frugiperda* larvae were parasitized by *Coccygidium luteum* (Brulle) in Ghana and Benin (Agboyi et al., 2020). *Chelonus bifoveolatus* (Szepligeti) was one of the predominant parasitoid species reported in West Africa (Koffi *et al*., 2020). Relatively low larval parasitism level reported in Uganda, averaging 9.2% (Otim *et al*., 2021). A similar result was reported in Mozambique, averaging 9.5% larval parasitism (Canico *et al*., 2020). Rate of parasitism of *Che. bifoveolatus* ranged from 0.8 to 16.7% in Uganda (Otim *et al*., 2021) it ranged from 0 to 35.6% in Ghana (Agboyi *et al*., 2020). In addition parasitism rate of *Chelonus* sp. was 10.9% in Senegal (Tendeng *et al*., 2019). Parasitism rate of *Coc. luteum* reported in Ethiopia, Tanzania, and Kenya were 4.6, 5.0, and 8.3%, respectively (Sisay *et al*., 2018).

The entomopathogens also play an imperative role to managing *S. frugiperda*. In Karnataka *Metarhizium rileyi* infections ranged from 10 to 62% across different states of natural field settings (Mallapur *et al*., 2018; Shylesha *et al*., 2018). ICAR-NBAIR (2020) recorded that *Beauveria felina* accounted for nearly 30% of natural *S. frugiperda* infections in Chikkaballapur, Karnataka. Several isolates of *S. frugiperda* nucleopolyhedrovirus (SfNPV) have been employed worldwide for the bio-control of *S. frugiperda*, achieving control efficacies above 80% (Gomez *et al*., 2013; Behle and Popham, 2012).

Bio-control agents of *S. frugiperda* in some Asian countries*:* Diverse groups of bio-control agents have been documented in Asian nations, including India (Shylesha *et al*., 2018), China (Tang *et al*., 2021), the Philippines (Navasero and Navasero, 2020), Pakistan (Riaz *et al*., 2024), Indonesia (Tawakkal *et al*., 2021), Malaysia (Singhamuni *et al.*, 2025), Sri Lanka (Bandara *et al*., 2021) and Nepal (Elibariki *et al.*, 2020) such as parasitoids, predatory insects, spiders, nematodes, and entomopathogens. Following *S. frugiperda*'s invasion as an agricultural pest in Asia, many scientists have studied and reported the diversity of its natural enemies, which are tabulated herein.

Parasitoids: Parasitoids represent a diverse group of natural enemies. In Asian countries, more than 50 parasitoid species have been documented in association with *S. frugiperda* (Table 1).

Table1. Parasitoids associated with *S. frugiperda* in Asian countries

Scientific name	Order	Family	Country	Reference
Egg parasitoids				

Telenomus remus (Nixon)	Hymenoptera	Scelionidae	India, Nepal Indonesia China Sri Lanka	Firake and Behere, 2020a, Navik *et al*., 2021,Keerthi *et al*.,2023 Elibariki *et al*.,2020 Sari *et al*., 2020 Liao *et al*., 2019, Tang *et al*., 2021 Bandara *et al*., 2021
Telenomus sp.	Hymenoptera	Scelionidae	India Indonesia	Shylesha *et al*., 2018 Tawakkal *et al*., 2021, Wahyuningsih *et al*., 2022
Trichogramma chilonis (Ishii)	Hymenoptera	Trichogrammatidae	Nepal, China India	Elibariki *et al*.,2020 Jin *et al*., 2021, Yang *et al*., 2022 Navik *et al*., 2021, Keerthi *et al*., 2023
Trichogramma sp.	Hymenoptera	Trichogrammatidae	India Indonesia	Shylesha *et al*.,2018 Tawakkal *et al*., 2021, Wahyuningsih *et al*., 2022
Trichogramma chilotraeae (Nagaraja and Nagarkatti)	Hymenoptera	Trichogrammatidae	Indonesia	Sari *et al*., 2021
Trichogramma pretiosum (Riley)	Hymenoptera	Trichogrammatidae	China	Jin *et al*., 2021, Yang *et al*., 2022
Trichogramma ostriniae (Pang & chen)	Hymenoptera	Trichogrammatidae	China	Jin *et al*., 2021
Trichogramma dendrolimi (Matsumura)	Hymenoptera	Trichogrammatidae	China	Jin *et al*., 2021, Yang *et al*., 2022
Trichogramma confusum	Hymenoptera	Trichogrammatidae	China	Jin *et al*., 2021
Trichogramma japonicum (Ashmead)	Hymenoptera	Trichogrammatidae	China	Jin *et al*., 2021
Trichogramma embryophagum (Hartig)	Hymenoptera	Trichogrammatidae	China	Jin *et al*., 2021
Egg –larval parasitoids				
Chelonus nr. blackburni (Cameron)	Hymenoptera	Braconidae	India	Sagar *et al*., 2022, Keerthi *et al*., 2023
Chelonus formosanus (Sonan)	Hymenoptera	Braconidae	India China	Firake and Behere, 2020a, Gupta *et al*., 2020a, Jindal *et al*., 2022, Sagar *et al*., 2022 Tang *et al*., 2020a
Chelonus munakatae (Munakata)	Hymenoptera	Braconidae	China	Li *et al*., 2019
Chelonus sp.	Hymenoptera	Braconidae	India, Philippines Indonesia Sri Lanka	Navik *et al*., 2021 Navasero and Navasero, 2020 Sari *et al*., 2023 Bandara *et al*., 2021
Larval Parasitoids				
Exorista sorbillans (Wiedemann)	Diptera	Tachinidae	India	Sharanabasappa *et al*., 2019
Exorista japonica (Townsend)	Diptera	Tachinidae	China	Ning *et al*., 2019
Peribeae sp.	Diptera	Tachinidae	India	Anandhi and

				Saminathan, 2021
Exorista sp.	Diptera	Tachinidae	Indonesia	Supeno *et al.*, 2021
Megaselia scalaris (Loew)	Diptera	Phoridae	China India	Tang *et al.*, 2021 Saranabasappa *et al.*, 2021
Coccygidium sp.	Hymenoptera	Braconidae	India	Sagar *et al.*, 2022, Keerthi *et al.*, 2023
Phanerotoma sp.	Hymenoptera	Braconidae	India	Saranabasappa *et al.*, 2021
Coccygidium melleum (Roman)	Hymenoptera	Braconidae	India	Sharanabasappa *et al.*, 2019
Cotesia ruficrus (Haliday)	Hymenoptera	Braconidae	India	Firake and Behere, 2020a, Keerthi *et al.*, 2023
Glyptapanteles creatonoti (Viereck)	Hymenoptera	Braconidae	India	Shylesha *et al.*, 2018
Microplitis manilae (Ashmead)	Hymenoptera	Braconidae	India Sri Lanka	Firake and Behere, 2020a Bandara *et al.*, 2021
Meteorus pulchricornis (Wesmael)	Hymenoptera	Braconidae	India	Gupta and Shylesha, 2021
Coccygidium transcaspicum (Kokujev)	Hymenoptera	Braconidae	India	Gupta *et al.*, 2020b
Cotesia glomerata (L.)	Hymenoptera	Braconidae	China	Ning *et al.*,2019
Cotesia sp.	Hymenoptera	Braconidae	India	Navik *et al.*, 2021
Apanteles sp.	Hymenoptera	Braconidae	Indonesia	Tawakkal *et al.*, 2021, Supeno *et al.*, 2021
Microplitis demolitor (Wilkinson)	Hymenoptera	Braconidae	India	Anandhi and Saminathan, 2021
Microplitis sp.	Hymenoptera	Braconidae	Indonesia	Tawakkal *et al.*, 2021, Sari *et al.*, 2023
Bracon brevicornis (Wesmael)	Hymenoptera	Braconidae	India	Ghosh *et al.*, 2020
Microplitis pallidipes (Szépligeti)	Hymenoptera	Braconidae	China	Tang *et al.*, 2020a
Microplitis prodeniae (Rao & Kurian)	Hymenoptera	Braconidae	China	Qin *et al.*, 2021
Microplitis similis (Lyle)	Hymenoptera	Braconidae	China	Tang *et al.*, 2020b
Euplectrus laphygmae (Ferrière)	Hymenoptera	Eulophidae	China	Tang *et al.*, 2020b
Euplectrus sp. *nr. Xanthocephalus* (Girault)	Hymenoptera	Eulophidae	India	Anandhi and Saminathan, 2021
Odontepyris sp.	Hymenoptera	Bethylidae	India	Sharanabasappa *et al.*, 2019
Euplectrus sp.	Hymenoptera	Eulophidae	Indonesia	Tawakkal *et al.*, 2021
Campoletis chlorideae (Uchida)	Hymenoptera	Ichneumonidae	India	Shylesha *et al.*, 2018, Sharanabasappa *et al.*, 2019, Navik *et al.*, 2021, Keerthi *et al.*, 2023
Campoletis flavicincta (Ashmead)	Hymenoptera	Ichneumonidae	Sri Lanka	Bandara *et al.*, 2021
Campolitus sp.	Hymenoptera	Ichneumonidae	India	Jindal *et al.*,2022
Temelucha sp.	Hymenoptera	Ichneumonidae	India	Sagar *et al.*, 2022, Anandhi and Saminathan, 2021, Keerthi *et al.*, 2023
Eriborus sp.	Hymenoptera	Ichneumonidae	India	Sharanabasappa *et al.*, 2019

			Indonesia	Supeno *et al.*, 2021
Charops sp.	Hymenoptera	Ichneumonidae	Indonesia	Tawakkal *et al.*, 2021, Sari *et al.*, 2023
Charops brachypterum (Gupta and Maheswary)	Hymenoptera	Ichneumonidae	Philippines	Navasero and Navasero, 2020
Diadegma semiclausum (Hellen)	Hymenoptera	Ichneumonidae	China	Ning *et al.*, 2019
Netelia sp.	Hymenoptera	Ichneumonidae	India	Firake and Behere, 2020a
Larval- pupal Parasitoids				
Metopius rufus (Ashmead)	Hymenoptera	Ichneumonidae	India	Firake and Behere, 2020a
Exorista xanthaspis (Wiedemann)	Diptera:	Tachinidae	India	Navik *et al.*, 2021
Indeterminate fly belonging to subfamily Exoristinae	Diptera:	Tachinidae	India	Firake and Behere, 2020a
Pupal parasitoids				
Ichneumon promissorius (Erichson)	Hymenoptera	Ichneumonidae	India	Firake and Behere, 2020a
Megaselia scalaris (Loew)	Diptera	Phoridae	China	Tang *et al.*, 2021
Indeterminate wasp belonging to tribe cryptini	Hymenoptera	Ichneumonidae	India	Firake and Behere, 2020a

Predators: Predators are capable of attacking various developmental stages of *S. frugiperda* (Abbas *et al.*, 2022). Numerous predators including insects and spiders have been documented throughout Asia (Table 2).

Table 2. Predatory insects and spider species associated with *S. frugiperda* in Asian countries

Scientific Name/ common name	**Family**	**Order**	**Host stage**	**Country**	**Ref.**
Predatory insects					
Forficula sp.	Forficulidae	Dermaptera	larvae	India	Shylesha *et al.*, 2018, Sharanabasappa *et al.*, 2019
Indeterminate earwig	Forficulidae	Dermaptera	Eggs&small larvae	India	Firake and Behere, 2020a
Earwig	-	Dermaptera	Larvae	Pakistan	Riaz *et al.*, 2024
Harmonia octomaculata (Fabricius)	Coccinellidae	Coleoptera	Larvae	India	Sharanabasappa *et al.*, 2019
Coccinella transversalis (Fabricius)	Coccinellidae	Coleoptera	Larvae	India	Sharanabasappa *et al.*, 2019
Cheilomenes sexmaculata (Fabricius)	Coccinellidae	Coleoptera	Larvae	Indonesia	Sari *et al.*, 2023
Micraspis discolor (Fabricius)	Coccinellidae	Coleoptera	Larvae	Malaysia	Jamil *et al.*, 2021
Ground beetle larvae	Carabidae	Coleoptera	Larvae	Indonesia	Tawakkal *et al.*, 2021
Ophionea nigrofaciata (Schmidt-Goebel)	Carabidae	Coleoptera	Larvae	Sri Lanka	Bandara *et al.*, 2021
Cicindela spp.	Cicindelidae	Coleoptera	Eggs and Larvae	India	Firake and Behere, 2020a
Staphylinidae larvae	Staphylinidae	Coleoptera	Larvae	Malaysia	Jamil *et al.*,2021
Paederus fuscipes (Curtis)	Staphylinidae	Coleoptera	Larvae	Sri Lanka	Bandara *et al.*, 2021

Eupeodes corolla (Fabricius)	Syrphidae	Diptera	Larvae	china	Hui *et al.*, 2021
Sycanus fallen (Stal)	Reduviidae	Hemiptera	Larvae	China	Hou *et al*., 2020
Sycanus dichotomus (Stal)	Reduviidae	Hemiptera	Larvae	Indonesia	Pebriansyah, 2023
				Malaysia	Singhamuni *et al.*, 2025
Cosmolestes sp.	Reduviidae	Hemiptera	Larvae	India	Firake and Behere, 2020a
Assassin bug	Reduviidae	Hemiptera	Larvae	Indonesia	Tawakkal *et al.*, 2021
Podisus maculiventris (Say)	Pentatomidae	Hemiptera	Larvae	India	Firake and Behere, 2020a
Andrallus spinidens (Fabricius)	Pentatomidae	Hemiptera	Larvae	India Malaysia	Firake and Behere, 2020a Jamil *et al.*,2021
Eocanthecona furcellata (Wolff)	Pentatomidae	Hemiptera	Larvae Larvae/Pupa	India Malaysia	Firake and Behere, 2020a, Keerthi *et al.*, 2020 Jamil *et al.*,2021
Arma chinensis (Fallou)	Pentatomidae	Hemiptera	Larvae	China	Tang *et al.*, 2019a
Picromerus lewisi (Scott)	Pentatomidae	Hemiptera	Larvae	China	Tang *et al.*, 2019b
Orius similis (Zheng)	Anthocoridae	Hemiptera	Larvae	China	Zeng *et al*., 2021
Polistes cf. olivaceus (De Geer)	Vespidae	Hymenoptera	Larvae	India	Firake and Behere, 2020a
Ropalidia brevita (Das & Gupta)	Vespidae	Hymenoptera	Larvae	India	Firake and Behere, 2020a
Dragonfly	-	Odonata	Larvae	Pakistan	Riaz *et al*., 2024
Damselfly	-	Odonata	Larvae	Pakistan	Riaz *et al*., 2024
Praying mantis	-	Mantodea	Larvae	Pakistan	Riaz *et al*., 2024
Green lacewing	Chrysopidae	Neuroptera	Larvae	Pakistan	Riaz *et al*., 2024
Spiders					
Lycosa sp.	Lycosidae	Areneae	Larvae	India	Firake and Behere, 2020a
Oxyopes birmanicus (Thorell)	Oxyopidae	Areneae	Larvae	India	Firake and Behere, 2020a
Oxyopus javanus	Oxyopidae	Araneae	Larvae	India	Anandhi and Saminathan, 2021
Marpissa sp.	Salticidae	Areneae	Larvae	India	Firake and Behere, 2020a
Rhene flavicomans (Simon)	Salticidae	Areneae	Larvae	India	Firake and Behere, 2020a
Jumping spider	Salticidae	Araneae	Larvae	India	Anandhi and Saminathan, 2021

Nematodes: Nematodes play an ecologically beneficial role and are essential for managing soil-dwelling insect pests, particularly pupae of the armyworms (Dillman *et al*., 2012). *S. frugiperda* pupae are highly susceptible to these entomopathogenic nematodes, with a reported infestation potential of approximately 23,000 per square foot (Prasanna *et al*., 2018).

Table3. Parasitic nematodes associated with *S. frugiperda* in Asian countries

Scientific Name/ common name	Host stage	Phylum	Class	Country	Ref.
Hexamermis cf. albicans (Von Siebold)	Larvae and pupa	Nematoda	Mermithidae	India	Firake and Behere, 2020a
Ovomermis sinensis (Hegmeier)	Larvae	Nematoda	Mermithidae	China	Sun *et al*., 2020b
Hexamermis sp.	Larvae	Nematoda	Mermithidae	Indonesia	Sari *et al*.,2023
Mermithid nematode	Larvae	Nematoda	Mermithidae	Philippines	Navasero and Navasero, 2020

Entomopathogens (Fungi, Bacteria, Viruses): Insect diseases are caused by entomopathogens, primarily bacteria, fungi, and viruses. Entomopathogenic fungi generally target *S. frugiperda* larvae and pupae. Through an insect's integument, fungal spores penetrate and develop within the body. After multiplying, they release specific toxins that degrade tissues and kill the insect (Abbas *et al*., 2022). According to Sujeetha and Sahayaraj (2014), when an insect is infected by entomopathogenic fungi, it ceases feeding, exhibits colour changes such as brown, reddish, green, or cream depending on the fungal species involved, and eventually dies. In natural fields, the pest acquires the virus by consuming contaminated maize leaves (CABI, 2021). These virions start to replicate in the nucleus after infecting the midgut's epithelial cells (Prasanna *et al*., 2018). Additionally, after spreading throughout the body cavity, these viruses begin to infect other tissues. The skin discoloration, blemishes, and decreased feeding are the primary symptoms of a Baculovirus infection (Valicente, 1988). The infected larvae are dark-colored, soft, and have secretions rich in polyhedrons, promoting the virus's propagation (Valicente, 1988).

Five entomopathogenic fungi species, one bacterial species, and two viruses were recorded as entomopathogens of *S. frugiperda* larvae and pupae in Asian countries (Table 4), with entomopathogenic fungi being the most widely distributed. *Metarhizium* and *Beauveria* species are the dominant types. *Bacillus thuringiensis* ranks as one of the most frequently used entomopathogenic bacteria against insects globally. It is also found in India, attacking *S. frugiperda* (Firake and Behere, 2020a; Sivakumar *et al*., 2020). Sf NPV represents one of the dominant viruses attacking *S. frugiperda* in Asia (Raghunandan *et al*., 2019).

Table 4. Entomopathogens associated with *S. frugiperda* in Asian countries

Scientific Name	Host stage	Country	Ref.
Entomopathogenic fungi			
Metarhizium (*Nomuraea*) *rileyi* (Farlow) Samson	Larvae	India	Shylesha *et al*., 2018, Manjula *et al*., 2019, Sharanabasappa *et al*., 2019, Firake and Behere, 2020a, Sivakumar *et al*., 2020
Beauveria bassiana (Balsamo) Vuillemin *Beauveria feline*	Larvae & pupae Larvae	India India	Firake and Behere, 2020a ICAR-NBAIR, 2020
Metarhizium sp.	Larvae	Philippines	Navasero and Navasero, 2020
Metarhizium sp.	Larvae	Indonesia	Sari *et al*.,2023
Metarhizium anisopliae	Larvae	India	Manjula *et al*., 2019
Beauveria sp.	Larvae	Philippines	Navasero and Navasero, 2020
Entomopathogenic Bacteria			
Bacillus sp.	Larvae	India	Firake and Behere, 2020a Manjula *et al*., 2019,

Bacillus thuringiensis	Larvae	India	Sivakumar *et al*., 2020
Entomopathogenic virus			
Spodoptera frugiperda Nuclear Polyhydrosis Virus (Sf NPV)	Larvae & pupa	India China	Raghunandan *et al*., 2019, Manjula *et al*., 2019, Firake and Behere, 2020a, Sivakumar *et al*., 2020 Li *et al*., 2024
Cytoplasmic Polyhedrosis Virus (CPV)	Larvae	India	Manjula *et al*., 2019

Significance of the conservation of natural enemies: These findings highlight the presence and vital role of indigenous bio-control agents in suppressing invasive species, acting as the first line of defence. This occurs because locally available bio-control agents of closely linked pest species often broaden the host range and contribute substantially to the control of invasive pests naturally (Vercher *et al*., 2005). The existence of native natural enemies associated with similar pest species, therefore, represents the initial protective barrier against new invasions. Hence, empowerment of the farmers with positive attitudes regarding native natural enemies to control invasive pest species is crucial for biodiversity conservation in agricultural fields. Evaluating the natural control inflicted by native bio-control agents is a significant approach in implementing a combined management approach for invasive insect pests (Firake and Behere, 2020a). Consequently, studies on local bio-control agents in newly invaded regions are of great importance.

Many biological control treatments are unacceptable to farmers because they require immediate solutions to pest problems in their cultivated fields (Ahissou *et al*., 2021). Therefore, most farmers tend to find quick methods other than bio-control. They do not much consider the sustainable management of pests in their field. A key limitation of biological control is that it acts more slowly than synthetic pesticides (Rioba and Stevenson, 2020). Nevertheless, biological control plays an essential role in conserving biodiversity while offering significant economic benefits (Epstein *et al*., 2021). As with traditional pest control methods, evaluating the effectiveness of bio-control agents must account for long-lasting effects in addition to short-terms outcomes (Ahissou *et al*., 2021).

Natural enemies provide an effective means of controlling *S. frugiperda*. Yet, many farmers remain unaware of their existence, and indiscriminate insecticide use often diminishes their populations. Since most farmers rely primarily on chemical control, enhancing their knowledge and attitudes toward natural enemies through targeted extension and education programmes is essential.

Conclusion: According to the literature survey, locally available natural enemies in various Asian countries have successfully established new associations with *S. frugiperda*. The literature review indicates that about 55 species of parasitoids, 28 species of predatory insects, 6 species of spiders, 4 species of nematodes, 7 species of entomopathogenic fungi, two species of entomopathogenic bacteria, and two species of entomopathogenic viruses have been recorded in China, India, Pakistan, Indonesia, Sri Lanka, the Philippines, Nepal, and Malaysia a few years after the invasion of *S. frugiperda*. These findings highlight the critical role that local natural enemies play in combating invading pest species, acting as the forefront of defence. This is because the locally available bio-control agents targeting closely linked pest species often expand their feeding range and contribute significantly to the natural management of invading pests. This review highlights the natural enemies that have established novel associations with *S. frugiperda* in several Asian countries, evaluates their potential as bio-control agents, and summarizes evidence of their successful application in globally. We hope that this synthesis of knowledge will encourage other affected Asian nations to adopt ecologically friendly suppression of *S. frugiperda*.

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