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REVIEW PAPER

Bio-ecology and management of *Spodoptera frugiperda* (Lepidoptera: Noctuidae): A review

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Abstract: *Spodoptera frugiperda* (Lepidoptera: Noctuidae) locally known as fall armyworm is an emerging pest of various crops (maize, cotton, and sugarcane). It has polyphagous feeding nature and is distributed throughout the globe depending upon the climatic conditions. The cob of maize is its preferred food and is heavily damaged during the high pest population. Feeding of its larvae can cause a characteristic skeletonizing or 'windowing' effect with excessive fecal pellets in maize. Being holometabolous, complete metamorphic changes occur during its developmental process i.e., egg, larva, pupa, and adult. Among all stages, only the larval stage is very dangerous for crop production. At optimum climatic conditions, it completes its life cycle very quickly. Temperature and humidity play an important role in influencing the life cycle duration of the pest. Several control strategies have been adopted by small and large communities or researchers to control this notorious pest all over the world like biological, chemical, botanical, physical, mechanical, and cultural operations. Due to the quick knockdown effect of insecticides, mostly farmers rely on the use of synthetic chemical pesticides, they are unaware that its use is a major threat to biodiversity and causes pest resistance to insecticides (Ali, et al., 2015). Keeping in view the drawback of chemical control, other alternative strategies such as mechanical, physical, botanicals, and biological can be promoted around the globe. *S. frugiperda* is an emerging pest in Pakistan since 2017, so biological control strategies should be devised. Among *Spodoptera* species, FAW (fall armyworm) *S. frugiperda* is different from others and closely resembles *S. litura* and implemented on a national scale that can control its growth, minimize its population and prevent the country from environmental pollution.

Keywords: Bio-pesticides, Emerging pest, Fall armyworm, Pakistan, *Spodoptera frugiperda*, *Trichogramma* spp.

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Introduction

Genus, *Spodoptera* is a very big genus (Ramzan et al., 2019) with 25 different species. Among reported species, *S. exigua*, *S. cilium*, *S. pectin*, *S. litura* (Faiz et al., 2015; Faiz et al., 2019), and *S. frugiperda* (Naeem-Ullah et al., 2019) are a major threat for the horticultural and agricultural crops throughout the globe. The fall armyworm, *S. frugiperda* is an emerging and invasive pest of various countries including Pakistan (Naeem-Ullah et al., 2019). It is a migrant insect pest with more than 80-100 alternate host plants (Clark et al., 2007; Abrahams et al., 2017; Cock et al., 2017; Food and Agriculture Organization [FAO], 2018) and flight up to 100 km in one night (Centre for Agriculture and Bioscience International [CABI], 2017a; Gilal et al., 2020). It belongs to the order Lepidoptera of the family Noctuidae (Naeem-Ullah et al., 2019).

Identification

S. exigua (Ramzan et al., 2019). The salient characteristics key of *S. frugiperda* has been described by Naeem-Ullah et al. (2019). On the forewing of adults, two white dots and an inverted Y-shaped dark yellow colored head of fully grown larvae have been reported by Niaz et al. (2018) similarly four black dots on the last body segments appear as a trapezium like structure (FAO, 2017).

Geographic distribution

It is mostly found in tropical and subtropical regions of the world (Abrahams et al., 2017; FAO, 2018; Prasanna et al., 2018). It has worldwide distribution including Brazil, USA (Prowell et al., 2004; Clark et al., 2007), Africa (Goergen et al., 2016), Pakistan (Niaz et al., 2018; Naeem-Ullah et al., 2019; Gilal et al., 2020), India (Sisodiya et al., 2018), Iran, China, Bangladesh, Thailand and Sri Lanka (FAO, 2019). likewise, other insects, its food preference among host plants is also different throughout the world (Majid et al., 2017; Shahid et al., 2017; Day et al., 2017; Kumela et al., 2019) like in some areas its food is rice, maize (Belay et al., 2012; Sidana et al., 2018), sorghum, sugarcane (Abrahams et al., 2017; Sibanda, 2017; Prasanna et al., 2018; Harrison et al., 2019), soybean, and cotton (Pogue et al., 2002; Nagoshi, 2014). The distribution of FAW (fall armyworm) is influenced by climate conditions (Pashley et al., 1985; Pair et al., 1988). Feeding habits can be modified depending upon crop availability and temperature that allowed the pest to migrate from Florida and Mexico to Canada (Hernandez-Mendoza et al., 2008). It has a large number of cultivated plant species (Casmuz et al., 2010) but the greatest damage was observed on maize and sorghum (its main hosts) as well as on cotton and soybean (Hardke et al., 2015).

Biology

Females of *S. frugiperda* can lay eggs on the lower surface of leaves in a cluster up to 100-300 numbers. Eggs hatch within 2-10 days and young ones pass through six larval instars with the larval developmental period of 14-21 days. Pupae are reddish-brown in color and pupation took place 1-3" deep in the soil, between the leaves, or in an earthen cell with a period of 9-13 days, and adults emerged (CABI, 2017b). The mating of adults occur by releasing sex pheromone by female, and the life cycle of *S. frugiperda* is completed in 26-46 days depending upon the climatic conditions, however biological parameters regarding development differed concerning plant species they feed. The number of host plants reported for *S. frugiperda* is higher when compared to other congeneric species of agricultural importance such as *Spodoptera albula* (Walker) (65), *Spodoptera cosmioides* (Stoll) (126), *Spodoptera dolichos* (Fabricius) (94), and *Spodoptera eridania* (Stoll) (202) (Montezano et al., 2013; CABI, 2020).

Ecology and damage symptoms

Insect pests badly affect the yield productivity (Shahid et al., 2015) and quality of the product however, the mode of damage differs among plant species (Shahid et al., 2017). The preferred host plant of *S. frugiperda* is maize and its larvae damage the leaves and corn cob as shown in Fig. 1. Both temperature and humidity are very important environmental factors that affect the growth and development of *S. frugiperda* under natural as well as artificial conditions (Du Plesis et al., 2020). The effect of different temperatures (32, 30, 26, and 22 ± 1°C) on all stages of *S. frugiperda* demonstrated that the most favorable temperature for the growth and development of *S. frugiperda* was 26- 30 °C with a minimum temperature threshold below 10 ºC (Stokstad, 2017).

The temperature has a significant influence on the duration of *S. frugiperda*'s life cycle. Capinera (2002) reported that *S. frugiperda* completes its life cycle in about 30 days during the summer, 60 days in spring and autumn, and 80 to 90 days during the winter. The number of generations occurring in an area varies with the appearance of the dispersing adults. Up to eight generations per year can, however, occur in maize fields in tropical areas (Busato et al. 2005). According to Johnson (1987), *S. frugiperda* is a tropical pest that does not have the ability to diapause when temperatures decrease. It has, however, been reported that this species may survive mild winters (Johnson, 1987). The lower temperature for optimal growth was set to 25 °C as suggested by Valdez-Torres et al. (2012). The upper optimal temperature for growth was set to 30 °C (Simmons & Rogers, 1994), and the maximum temperature was set at 39 °C, near the threshold of 39.8°C reported by Valdez-Torres et al. (2012). Fall armyworm does not diapause and cannot survive the winters in temperate areas (Johnson, 1987). Diapause was therefore not included in this model. A temperature threshold model of Cold Stress was used, with a 12 °C threshold. With these settings, cold stress limits the potential range in the USA to the areas where *S. frugiperda* has been reported to survive winter months, in south-western Texas and southern Florida (Johnson, 1987). Heat stress parameters were set to allow persistence in all of the known locations from which it has been observed. The threshold of 39 °C is the same as the upper-temperature limit for development. The threshold annual heat sum required for population persistence (PDD) was set to 600 degree days above 12 °C, the lower temperature limit for development. Warm, humid growing seasons with heavy rainfall favor its survival and population buildup because it cannot develop at temperatures below about 10°c (Stokstad, 2017). Adults of FAW are nocturnal (CABI, 2017a). After a pre-oviposition period of three to four days, the female normally deposits most of her eggs during the first four to five days of life, but some oviposition occurs for up to three weeks (Prasanna et al., 2018). Duration of adult life averages about 10 days, with a range of about 7 to 21 days (Capinera, 2000) and due to the duration of the life cycle, 2 to 10 generations can be completed in each cropping cycle depending on climate. It is reproductively efficient in tropical areas, where the warmer temperature allows more generations per year compared to temperate areas that may have two or fewer generations in a year.

Economic importance of *S. frugiperda*

The larva is the damaging stage of *S. frugiperda*, its later instars can damage the whole leaf of the crop especially, maize. As shown in Fig. 1, severe feeding of young larvae causes a characteristic skeletonizing or 'windowing' effect (Sisodiya et al., 2018; Chormule et al., 2019a) with excessive fecal material is the major symptom of its damage (Chormule et al., 2019b). The growing point of plant killing even 100% death of plants occurred. The corn ear can completely or partly be destroyed by the severe attack of larvae (RicBessin, 2004; Bokonon-Ganta et al., 2003), ears become susceptible to aflatoxin (FAO, 2017) and unfit for human consumption (Chimweta et al., 2020).

Integrated pest management

Across the globe different integrated pest management (IPM) strategies are being employed for the control of insect pests of economic crops. Integrated strategies include host plant resistance, cultural, physical, mechanical, biological, botanical, and chemical control tactics. Detail of the control methods for the management of *S. frugiperda* is given below:

Monitoring methods

It is an effective tool for the assessment of the insect pest (Shahid et al., 2019) and to control insect populations below economic injury level (Naharki et al., 2020). It can prove the best and effective tool to avoid *S. frugiperda* spread and establishment (Prasanna et al., 2018). The pest population can be minimized by using pheromones and light traps (Rajbhandari et al., 2019; Gebreziher & Gebreziher, 2020).

Host plant resistance

Host plant resistance also plays an important role in managing insect pest attacks (Shahid et al., 2012; Shahid et al., 2018). Morphological and biochemical traits of plants not only deter the attack of insect pest herbivory but also contribute to yield productivity (Rahman et al., 2013; Farooq et al., 2014).

Cultural control

Various cultural practices have been adopted by researchers to control *S. frugiperda* in the world, such as avoiding late crop sowing; intercropping; destruction of crop residues; crop plowing after crop harvesting to expose the larvae and pupae on the soil surface; early visual detection; and pest movement prevention from infested to non-infested areas (Shahid et al., 2014). The fall armyworm population can be decreased in various crops by adopting these cultural practices. Removal and destruction of egg masses and small gregarious larvae, burning of stubbles can reduce all stages of pests like adults, eggs, larva, and pupa in the field. The coming generation of pests survives even after harvesting reduces by the burning process (Assefa, 2018). The application of ash, sand, and soup directly to whorls can minimize the pest population. Some researchers have recommended fish soups that attract ants that eat the larvae of *S. frugiperda* (Murray et al., 2019). The maintenance of plant diversity in the field is a very important factor to control the pest population (Tippannavar et al., 2019; Tambo et al., 2020). It had been reported by many researchers that pest population increased through monocropping while decreased with intercropping with other crops such as leguminous (Harrison et al., 2019; Rajbhandari et al., 2019). Khan et al. (2018) reported that Napier grass (*Pennisetum purpureum*) proved the best attractant trap crop while Desmodium grass (*Desmodium spp.)* as a repellent to *S. frugiperda*. Push and pull strategy has proved the best approach against *S. frugipera* (Midega et al., 2018).

Mechanical control

This technique is useful at a small level and farmers can manage the pest population by regular monitoring in the field. The early infestation can be controlled by the use of protective measures but later and high infestation of pests cannot be controlled until reaching the economic threshold level (Foster, 1989; Evans & Stansly, 1990; Dal Pogetto et al., 2012). These can be adopted to control pest populations such as fertilization (organic and inorganic manure and fertilizers), mulching, minimum tillage, intercropping, and reduce weed management. The locally available toxic substances such as sand, soil, lime, soaps, wood ash, and oils have been applied against larvae of *S. frugiperda* (Hruska, 2019) and gave the best control (Ebeling, 1971; Korunić, 2013).

Biological control

This is an effective and eco-friendly approach to control insect pests with a non-negative impact on humans, animals, biological fauna, and the environment (Shahid et al., 2007; Arif et al., 2011). Rodents, birds, ladybird beetles, bugs, ants, and flowers bugs are predators of *S. frugiperda* (Sana-Ullah et al., 2011; FAO, 2018; Farooq et al., 2018) in various crops like sorghum and maize (Cruz, 2007; Sueldo et al., 2010; Abrahams et al., 2017; Farooq et al., 2020). *Chelonus texanus*, *Cotesia marginiventris*, *Archytas marmoratus* and *Elenomus remus* are important parasitoids of different stages of *S. frugiperda* (Cave, 2000). *Orius insidiosus* has been reported as an egg and larval parasitoid of *S. frugiperda* (Isenhour et al., 1990). *Trichogramma* species have been distributed all over the world (Abrahams et al., 2017) and they are extensively used against various insect pests especially *Spodoptera* spp. like *S. frugiperda* of various horticultural and agricultural crops (apple, cotton, rice, corn). The population of parasitoids depends upon climatic conditions, availability of prey, and type of the crop (Parra et al., 2016). The entomopathogenic fungi (*Erynia radicans*, *Metarhizium anisopliae*, *Fusarium solani*, *Beauveria bassiana*, *Nomuraea rileyi*) (Rios-Velasco et al., 2011; Hernandez-Trejo et al., 2019), viruses (Nuclear polyhedrosis virus), and bacterium (*Bacillus thuringiensis*) have been reported as best and effective control against pest (Gardner et al., 1984; Lezama-Gutie´rrez et al., 1996; Wraight et al., 2010; Faria et al., 2015; Liu et al., 2019; Li et al., 2020).

A study was conducted to check the efficacy of entomopathogenic nematodes (EPNs) such as Heterorhabdidae and Steinernematidae against *S. frugiperda* under laboratory conditions (Grewal et al., 2005; Zamora & Markelyn, 2019). They concluded that nematodes were found lethal and virulent against *S. frugiperda* (Andalo et al., 2012a). After 48 hours of post-treatment, EPNs were found more toxic with 65% mortality of larvae (Zamora & Markelyn, 2019). Another study was conducted to check the toxicity of entomopathogenic nematodes (*Heterorhabditis bacteriophora*) against prepupae and pupae of *S. frugiperda* under laboratory conditions. The study investigated 92% and 80% mortality of prepupae and pupae of *S. frugiperda*. The adult longevity (15-30%) and fertility (20%) of pests can be reduced by the infestation of ectoparasitic nematodes, *Noctuidonema guyanense* (Simmons & Rogers, 1994; Salazar-Gutie´rrez et al., 2017). The complete list of natural enemies for different stages of *S. frugiperda* has been given in Table 1.

Botanical control

The pest resistance to insecticides can be minimized (Arain et al., 2018) by the application of plant materials (Khater, 2012). Botanical control has been widely used against insect pests in developed countries (Batista-Pereira et al., 2006) due to its availability, affordability, and also because it is safe for humans, animals, and biological fauna (Schmutterer, 1988). Many plant extracts such as *Milletia ferruginea*, *Azadirachta indica*, *Croton macrostachyus*, *Jatropha curcas*, *Chrysanthemum cinerariifolium*, and *Nicotina tabacum* are widely used plant extracts against *Spodoptera* species especially *S. frugiperda* in various countries (Schmutterer, 1988) and they give maximum larval mortality (Silva et al., 2015). The feeding and growth of larvae have been reduced by the application of *Argemone ochroleuca* extracts (Martínez et al., 2017).

Fig. 1 Damage of *Spodoptera frugiperda* (CABI, 2018)

Chemical control

The application of poisonous chemicals to control insect pests is a widely used method on a large scale all over the world. Different types of chemicals (insecticides) with a different mode of action and entry as ingestion and contact have been used for the management of *S. frugiperda* (de Albuquerque et al., 2006). According to Azevedo et al. (2004), seed treatment is not the best approach to control *S. frugiperda*. Various insecticides (lambda-cyhalothrin, Malathion, permethrin, and chlorpyrifos) have been used to check their effectiveness against *S. frugiperda* in the laboratory as well as in field conditions. Clothianidin and thiodicarb were found more effective and gave maximum larval mortality than thiamethoxam, fipronil, and chlorpyrifos (Camillo et al., 2005). further studies depicted that Emamectin benzoate, Indoxacarb, Malathion, Flubendiamide, Methomyl, Chlorpyrifos, and Lufenuron gave better control against fall armyworm, *S. frugiperda* including; (Niaz et al., 2018).

Conclusion

The *S. frugiperda* has recently been becoming an invasive species and adopting the environmental conditions of Pakistan. It is spreading in many areas of Pakistan, so urgent management options are needed to control this pest. There is also a need to provide awareness among the farming communities about pest scouting, understanding the right time of pest attack on which stage of the crop, right time of management application, and low-cost agronomic practices implementation for sustainable management of the *S. frugiperda.* Further trials should be conducted to check the host plants life cycle at different temperatures in Pakistan. Agriculture Research institutes and Academia should conduct experiments and Extension staff of the Government should timely transfer the result findings by educating the farming community about the pest. The plant population or diversity should be increased that can prove the best strategy in the enhancement of natural enemies. Intercropping is a very important strategy to control *S. frugiperda* such as maize with beans. The relationship of *S. frugiperda* with the weather (climate and temperature) is an important strategy for predicting *S. frugiperda* damage and distribution. A push-pull strategy like the cultivation of Napier grass and Desmodium grass with maize crop can prove the best management option of *S. frugiperda*. Biological fauna should be promoted and area-wise management would be the best option to control this pest.

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