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Invasion of *Spodoptera frugiperda* (Lepidoptera: Noctuidae), a global threat to maize crop: A review

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Abstract
Spodoptera frugiperda (JE Smith) (Lepidoptera: Noctuidae), commonly known as fall army worm (FAW) holds considerable importance among devastating pests in terms of crop yield loss and negative impacts on the economies of both developing as well as developed countries. This alien invasive insect feeds on more than 350 host plant species in addition to maize crop. Moreover due to its voracious nature, this pest (native to North and South America) has spread other continents also (Africa, Asia, Europe and Australia) and therefore has become a major threat to maize crop. In Asia, FAW was first reported in India in mid-2018 in the maize fields of South Karnataka where it invaded the maize fields within a short period of two months. Now it has been widely spread across other Asian countries like Bangladesh, Sri Lanka, Myanmar, Thailand, Indonesia and Nepal. The FAW is difficult to control, manage, or eradicate by the use of any single method, because this pest is polyphagous in nature, multiplies fast, has a short life cycle and migrates at very fast rate, and lacks the diapause growth phase. Moreover, the unsuccessful and misuse of pesticides to control FAW has led to emergence of resistance, resurgence and increased production. Thus, it has become challenge for the scientific community and administrators to develop management strategies to control or destroy the pest. The longterm management and keeping the pest population below economically injury level is essential because it is practically impossible to completely eradicate the pest. Therefore, there is an urgent need to develop ecologically sustainable, socially acceptable and economically profitable integrated pest management strategies to control FAW in India and Asia. In view of this, the present review focuses on its life cycle and different management strategies (cultural, physical, mechanical, botanical and chemical methods) to conquer the pest from causing economic damage in maize.

Keywords: Fall armyworm, Maize, incidence, symptoms, lifecycle, Integrated pest management

1. Introduction and Distribution

Maize (*Zea mays* L.) is one of the most important cultivated cereal crops all over the world after wheat and rice with many uses including food, feed and an important substrate for biofuel production (Daudi *et al*., 2021) [19]. However, the production of maize is always under constant threat due to its several insect pests such as aphids, cut worm, stem borer, shoot fly, fall army worm (FAW) etc. Among these, the FAW [*Spodoptera frugiperda*,(Smith) (Lepidoptera: Noctuidae)], the most invasive pest of maize crop is regarded as super pest because of its ability to survive in wide range of habitats, high fecundity, wide host range, without diapause and gluttonous characteristics. Moreover, the high migration capacity of the pest (about 100 km / night) has enhanced its spread all over the world within a short period of time (Johnson, 1987). Although, FAW is native to tropical and subtropical regions of the America, but now it has reached Europe, Africa and Asia also. Within the last three years, it has invaded 47 African and 18 Asian countries. In India, this pest was first sighted on 18 May 2018 in Shivamogga, Karnataka and later infested other states (Bihar, Chhattisgarh, Gujarat, Maharashtra, Odisha, Tamil Nadu, Telangana and West Bengal) within a year (ICAR-NBAIR, 2018; EPPO, 2019) [37,]. Till 2018, the Indian authorities were unaware of the presence of fall armyworm and therefore, Indian states suffered huge yield losses (up to 58%) due to this invasive pest. Later, the pest was also reported from other crops such as sugarcane and sorghum in India (Saranbassappa *et al*, 2018; Chimweta *et al*, 2019). In Punjab state of India, FAW was first noticed in the farmers' fields in August 2019 where the insect infested late sown fodder maize in various districts such as Jalandhar, Hoshiarpur, Ropar, Pathankot, Patiala and Fategarh Sahib. Recently, FAW damaged 4500 acres of summer maize crop in Ropar district of Punjab. FAW is present in all maize growing states but not in northern Jammu, Srinagar and Himachal Pradesh (Rakshit *et al.* 2019) [59] (Fig. 1). Between February 2020 to April 2021, and May 2020, FAW invaded Australia, Timor Leste, Mauritania, and the.

United Arab Emirates, Syria, Jordan and Papua New Guinea, New Caledonia, Canary Islands of Spain in Europe (FAO, 2021;https://www.fao.org/fall-armyworm/monitoring-tools/faw-map/en/). As of now, FAW has migrated from the Americas to over 70 countries and has shown a high level of ecological adaptation with huge destruction to maize crop all over the world (Groote *et al.*, 2020) [42]. Till date, there is no single effective method of its control and therefore, there is a huge need to develop effective management strategies to combat with this pest. Thus, this review paper is an effort to discuss the nature of damage, life cycle and management of FAW.

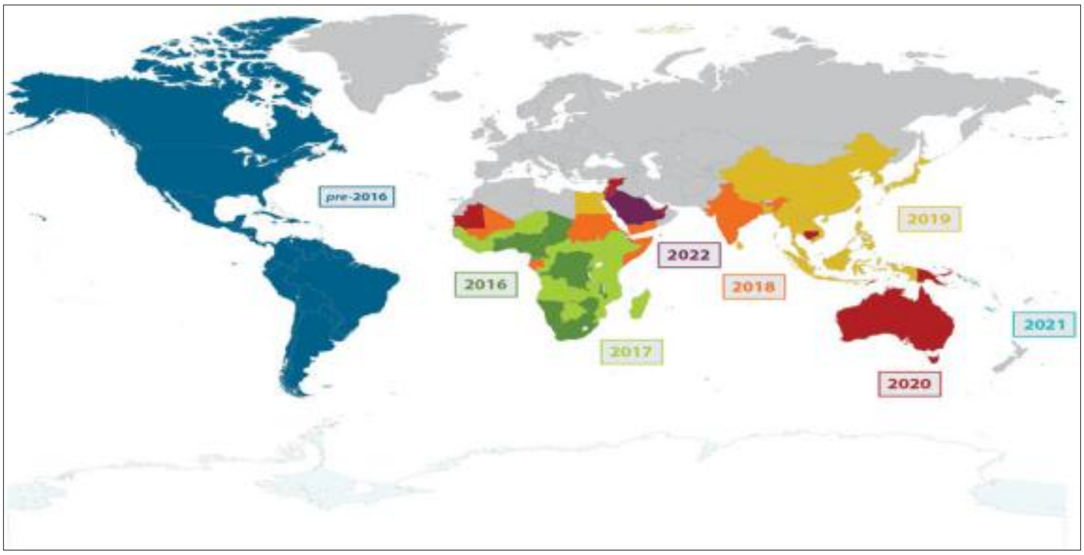

Fig 1: Infestation of Fall Army Worm in different areas of world since 2016 to 2022 (Source: FAO, 2022)

2. Taxonomy

The genus *Spodoptera* was first described by Guenee in 1852 and then three Genera *Spodoptera*, *Laphygma* and Prodenia were synonymized to *Spodoptera* (Bayer, 1960) [6]. There are two strains of FAW; Rice strain and Corn strain, where rice strain feeds on rice crop and other grasses whereas the corn strain feeds on maize, cotton and sorghum crops (Nagoshi *et al.*, 2007; CABI, 2020) [53]. These strains are morphologically similar but can be differentiated at the molecular level. The detailed classification of fall armyworm (*S. frugiperda*) is represented in table 1.

Table 1: Detailed Classification of Fall Armyworm (*S. frugiperda*)

Kingdom	Animalia
Phylum	Arthopoda
Subphylum	Hexapod
Class Insecta	Insecta
Subclass	Pterygota
Order	Lepidoptera
Genus	*Spodoptera*
Species	*Frugiperda*

3. Host Profile and Preferences

S. frugiperda is a devasting polyphagous pest with wide host range in dispersed habitats all across the globe. The number of host plants reported for *S. frugiperda* is higher when compared to other congeneric species of agriculture importance such as *Spodoptera albula, Spodoptera cosmiodes, Spodoptera dolichos* and *Spodoptera eridania* (Montezano *et al.* 2013) [51]. this Lepidoptera shows a definite preference for the Poaceae family among which the most common hosts are wild (bent grass, Johnson grass, *Cyperus* sp., morning glory etc.) and cultivated grasses (maize, rice, sorghum, sugarcane); other crops such as apple, papaya, peach, strawberry and number of flowers (Rwomushana, 2019) [62]. Along with the preferential host plants, FAW use some of the other host plants only to maintain their populations under adverse climatic conditions or in the absence of preferential hosts (Casmuz *et al.*, 2010) [12]. In another study, Montezano *et al.*, 2018 [50] reported the incidence of *S. frugiperda* in 353 different plant species belonging to 76 botanical families. These data suggest that FAW can produce several generations in a single season due to availability of suitable host plants all over the world.

4. Damage and Symptoms

FAW produces several generations per year and can attack maize from its vegetative to reproductive phases (FAO, 2018) [25]. From all the developmental stages of *S. frugiperda*, the larval stage, being voracious in nature, is the most annoying as it causes significant damage by consuming foliage of economically important cultivated host crops (Ayra-Pardo *et al.*, 2021) [4]. Young larvae start feeding the leaf tissues by scrapping and skeletonising the epidermis layer and secrete a silken web. In later stages, the larvae enter into the whorls and start feeding leaves which lead to the formation of holes and excrete large amount of faecal matter in the plant whorl (Fig. 2). Later it feed on primordial shoot and tassels and results in dead heart symptoms (Shylesha *et al.*, 2018) [65]. At very high population levels, larvae can also penetrate maize ears as well as cob and cause direct damage to the whole crop. In addition, the marching behaviour of pest, similar to that of the army, causes havoc loss to the crops that come in its path and lead to extensive defoliation of plants (FAO, 2019; CABI, 2019). The pest can invade large area of cultivated crops in a very short time due to its migratory behaviour. Moreover, the continuous fecundity behaviour of FAW is also expected to be responsible for adverse damage to the crops (Goergen *et al.*, 2016) [34].

Fig 2: Pictures showing typical damage by FAW on maize crop; (2a) Maize leaf damage with shot holes (2b) Leaf damage with saw like frays (2c and 2d) Cob damage by FAW

5. Life Cycle of Fall Armyworm

To successfully control the FAW, the knowledge of the life cycle of the pest is very important as it provides understanding of its activities. This insect has complete metamorphosis which includes egg, larvae (6 instars), pupa and adult (moth). FAW completes its life cycle within 30 days when favourable conditions (temperature and preferable host plant) are present (Fig. 3). It may takes about 60 days in the spring and autumn (Chhetri and Acharya 2019 and Radzevičius, *et al*., 2016) [14, 58], however, in winter season this period may extend up to 80 to 90 days (Sharanabasappa, *et al.*, 2020; Capinera, 2002) [72, 10].

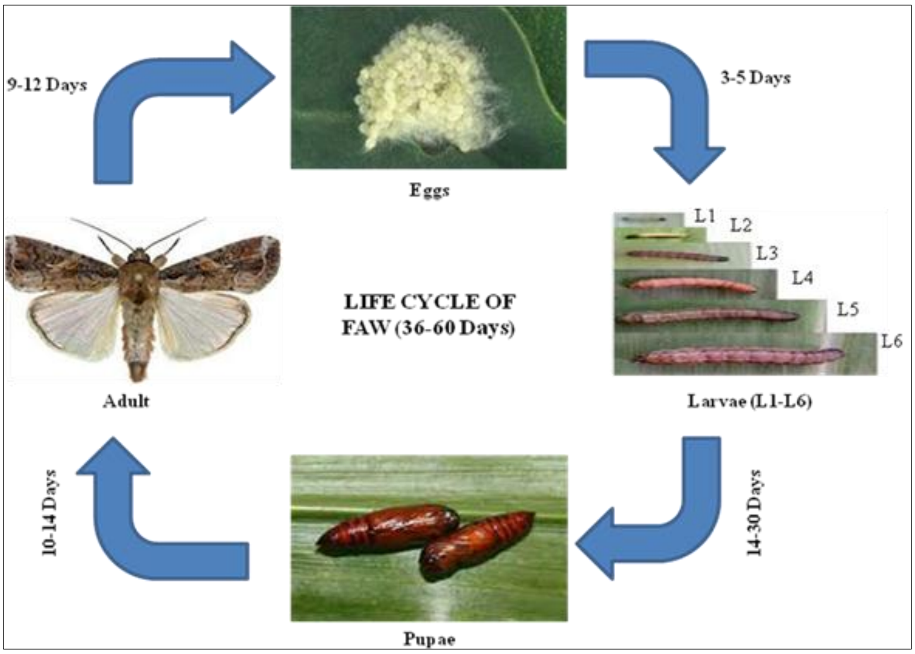

Fig 3: Different stages in life cycle of FAW

5.1 Eggs

The adult females of FAW, like most noctuidae are short lived but have high fecundity rate. Their oviposition period ranges from 3-5 days. A female generally laid eggs in clusters on the top of leaves, underside of the leaves, near the base of the plant and in the whorl. In her life span, an adult female lays around 1500-2000 eggs where the number of eggs per cluster can varies from 100 to 200 (Prasanna *et al*., 2018) [57]. These eggs are covered in protective scales rubbed off from the moth's abdomen after laying the eggs, which gives a mouldy appearance. The dome shaped flattened eggs change their colour from pale yellow to creamy white and then light brown (Kandel and Poudel, 2020) [41]. However they turn dark brown in colour just before hatching. Under favourable conditions where temperature is around 20-30 ^{o}C, the duration of the egg stage is only 2-3 days (Akeme *et al.*, 2021; Du Plessis *et al.*, 2020) [1, 23].

5.2 Larvae

The larval stage which includes 6 instars (of different colour and size) ranges between 14-30 days depending upon the temperatures (Castro *et al.,* 1988; Sharanabasappa *et al.,* 2018; Capinera, 2020) [13, 73]. The newly hatched first instars larva is green in colour with black head and then turns into orange colour in second instars. In third instars, the dorsal surface turns brownish in colour with start of formation of lateral white lines. From fourth instars onwards, larval head is reddish brown with mottling of white lines, and the brownish body bears white sub dorsal and lateral lines (CABI, 2017). The larval size ranges from 1mm to 45 mm for the first instars to sixth instars larvae respectively (Prasanna *et al*., 2018) [57]. There is distinctive white inverted Y suture on the forehead and rough or granular epidermis of the mature larva (Pitre and Hogg 1983) [56]. A set of 4 elevated dark coloured spots bearing spines, occurs this stage of FAW is the most destructive life stage as the larvae have chewing and biting type of mouth parts. On the upper surface of the body and is the most distinctive identification feature of FAW (Fig. 4).

Fig 4: Typical morphological features of FAW Larvae; a, b show the 'Y' shape on the head, c shows the four black flecks and d shows the curling before pupation (Source: Song *et al*., 2020)

5.3 Pupae

The fully grown caterpillar stops feeding and drop to the ground approximately after 14 days (Sharanabasappa *et al.* 2021) [76] where it burrow 2-8 cm into the soil before pupating. The mature larva then form 20-30 mm long loose oval shaped cocoon by tying together soil and leaf debris. The reddish brown pupa measures 14 to 18 mm in length and about 4.5 mm in width (Bhatti, 2020) [8]. The temperature of the environment plays important role in the duration and survival of pupae stage which lasts for about 8 to 9 days during warmer months whereas the same extends up to 20 -30 days in cooler months (Akeme *et al* 2021) [1]. However, FAW does not diapauses even at the temperatures where frost occurs. The male and female pupa can be distinguished on the basis of distance between genital opening and anal slot where this distance is more in female pupa than in the male pupa (Sharanabasappa *et al.,* 2021) [76].

5.4 Adult

At the end of the pupation, adult emerges. The adult male is 1.6 cm in length with 3.7 cm wingspan whereas the body length of adult female is 1.7 cm with wingspan of 3.8 cm (Akeme *et al*., 2021) [1]. The forewings can be used to distinguish between adult male and female moths. In case of male, the forewing is mottled with gray and brown shades along with triangular white spots at the tip and near the centre of the wing. The female forewings are less distinctly marked with consistent greyish brown to a fine mottling of grey and brown. Both the sexes have a hind wing which is iridescent silver-white with a narrow dark strip border (Prasanna *et al.,* 2018) [57]. These adults show nocturnal behaviour which means they are active at nights in the warm and humid habitat (Ibrahim and Jimma, 2018). After emergence, the adult life span ranges between 7 to 21 days with an average of 10 days (Akeme *et al.,* 2021) [1]. The longevity period of adult female includes pre-oviposition, oviposition and post-oviposition periods ranging from 3 to 4, 2 to 3, and 4 to 5 days, respectively (Kranti *et al.,* 2021) [74]. The female normally deposits most of her eggs early in life and they are typically attracted to the fields of late-maturing corn to lay their eggs. In captivity, each female lays 835 to 1169 eggs with an average of about 1000 eggs. The total life cycle of male and female fall armyworm ranges from 32 to 43 and 34 to 46 days, respectively (Sharanabasappa *et al*., 2018) [73]. The average female longevity is 9-12 days as compared to male with a range of 7-9 days.

6. Integrated Pest Management

The management of FAW using only a single approach has proven unsuccessful so, different strategies (which are holistic and multidisciplinary) can be used in an integrated manner to control FAW population (Bista *et al*., 2020) [75]. In this regard, an integrated pest management (IPM) has emerged as a successful alternative approach to manage FAW infestation. IPM is an integrated strategy of pest control which aimed at prevention of insect pest and its infestation through integral techniques such as cultural, physical, mechanical, and biological and chemicals. IPM application ensures the sustainable and economical method with reduced risk to environment and human health (Bateman *et al.,* 2018) [62]. Under IPM approach, the best and the most effective key to FAW management is to detect the fall armyworm infestation before they cause economic damage. It is recommended to apply an effective control measure to prevent further damage if in maize 5% of seedlings are cut or 20% of whorls of small plants are already infested with FAW (Fernandez, 2002) [28]. The main strategies of IPM which are used to manage FAW can be divided into two categories:

1. Preventive Methods
2. Curative methods

The effectiveness of these methods to eliminate the pest is highly dependent upon their timing of application along with the time of day for application and the stage of the life cycle of the pest (Assefa, 2018; Assefa and Ayalew, 2019) [2-3]. The FAW cause severe damage to maize at its early growth stage (larval stage, especially, second and third instar). Therefore, the proper management of pest at larval stage is the most effective control measure when applied at proper time (morning and evening).

6.1 Preventive Methods

6.1.1 Monitoring

The first step which holds significant importance in better management of FAW is the application of appropriate monitoring methods. The regular monitoring is the basis for integrated pest management, decision making and implementation of the best control strategy. The use of monitoring methods can help to indicate the presence and absence of a given pest at locations. The FAW monitoring can be done using different techniques such as regular field inspection, light traps and pheromone traps (Haftay and Fissiha, 2020; Gebreziher 2020) [35, 33]

6.1.2 Scouting

The detection of fall armyworm infestation before it causes economic damage is the key to their management (Assefa and Azalea, 2019) [3] and therefore scouting should be started in 'W' manner as soon as the maize seedling emerges. It is indispensable to regularly scout crop fields every 3-4 days for 5-7 weeks after planting and if FAW is detected from scouting, then application of control measures becomes obligatory. For instance, on maize, if 5% of seedlings are damaged, 10% of mid whorls stage are freshly damaged or 20% of late whorls are infested with FAW, then action should be taken to prevent further damage (Fernandez, 2002) [28].

6.1.3 Cultural control

Cultural control methods, an integral component of FAW management strategy mainly involves the application of proper agronomic practices. This method is given first priority over any other control methods. Deep ploughing before sowing (exposure of FAW pupae to natural enemies), clean cultivation (FAO, 2018) [25], use of resistant varieties, avoid late sowing (because late sown crops are heavily attacked by FAW than those of the early plantings) (Biblo, 2019), avoid of late maturing varieties (Chhetri and Acharya, 2019) [14], proper seed depth, balanced use of fertilizers, proper irrigation and removal of unwanted plants (damaged plants or wastes) are some of the cultural methods which can minimize the occurrence and infestation by FAW (FAO, 2018; Acharya *et al.*, 2020) [25, 14]. In addition, burning stubbles and crop residues in attacked fields could destroy unhatched eggs, larvae, pupae and adults (Assefa, 2018) [22]. Besides these, intercropping or rotating maize with other non-host crops such as Maize + black gram / pigeon pea / green gram / beans are efficient method to control FAW (Hailu *et al*., 2018) [36]. According to Assefa and Ayalew, 2019 [3], cultural control methods contribute 56% share in management of FAW.

6.1.4 Push-pull technology (PPT)

The International Maize and Wheat Improvement Centre (CIMMYT) developed a new eco-friendly method of pest management known as Push-Pull Technology (also called PPT). It is based on the behavioural manipulation of insect pests and their natural enemies based on semi chemicals particularly kairomones and allomones (Cook *et al*., 2007) [18]. In PPT, CIMMYT used Silver leaf desmodium (*Desmodium uncinatum*, a push plant or repellent plant) as an intercropping plant that repels or deters insect pests by producing allomones. On the other side, Napier- grass (*Pennisetum purpureum*) or *Brachiaria* (*Brachiaria brizantha* × *Brachiaria ruziziensis*) are used as attractive trap plants because of kairomones production by these plants. Further, they are highly perceptible and attractive to a pest and therefore, grown as a border crop around intercropped field to assist in pest control (Fig. 5) (Cook *et al*., 2007; Khan *et al*., 2010; Zhang *et al*., 2013) [8, 77, 78]. The push plant release volatile chemicals such as (E)-4, 8- dimethyl-1, 3, 7-nonatriene and (E)-β-ocimene that repel female moths of FAW, whereas kairomones released by the pull plant are more attractive than maize to adult moths of FAW and stem borer, thus facilitate FAW at concentrations in the pull plant. Several research reports have shown the effectiveness of PPT for the control of FAW (Khan *et al.*, 2011; Hailu *et al.*, 2018; Kumela *et al.*, 2019 and Haftay and FIssiha, 2020). This technology of push and pull plants is proven to be climate-smart, eco and farmers friendly, affordable control method and can be integrated with other control methods for more efficiency in controlling the pest.

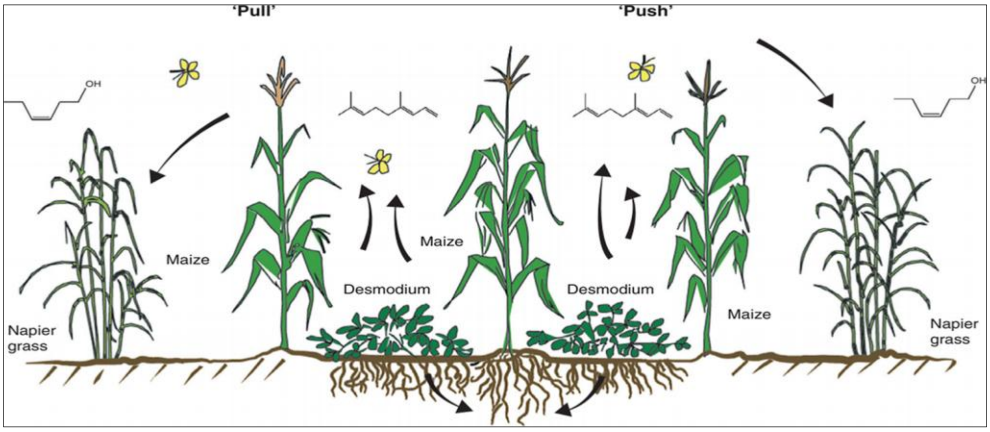

Fig 5: Illustration of a push-pull Farming Systems. Source: Pickett *et al*. (2014) [79]

6.1.5 Physical and Mechanical Control

Physical and mechanical control methods as preventive measures also play important role in the management of fall armyworm. These methods include hand picking and destruction of egg masses and gregarious larvae by immersing in kerosene water or by crushing them (Firake, 2019; Hruska, 2019) [30, 80]. These methods are commonly used by growers as a first line of defence in most of the countries. Although these measures are time-consuming but can reduce the pest population when practiced during the early developmental stages of maize. These methods also use some commonly available substances such as urine, salt, detergents, oils and soaps (Rwomushana *et al*., 2018; Hruska, 2019; Yigezu and Wakgari, 2020) [62, 80, 71]. FAO promoted another inexpensive and effective management option which includes the application of dry sand or ash directly to the whorls of infested maize plants. Sand kill fall armyworm larvae, *via* roughness or absorption of cuticle wax, thus cause larval desiccation (FAO, 2017; Hruska, 2019) [26, 80]. The Sand ecosystem containing micro-organisms such as *Beauveria bassiana* (Balsamo) and *Bacillus thuringiensis* may also play crucial role in control of fall armyworm (Ramirez-Rodriguez and Sánchez-Peña, 2016) [61]. The adoption of mechanical control methods contributes 54% in FAW management (Assefa, 2018) [2].

The incidence of fall armyworm can also be managed by installing pheromone traps @ 5 / acre in maize crops (season and off-season) (Firake, 2019) [30]. As the use of these traps is simple, FAO (2017) [26] has recommended for scaling of sex pheromone traps that attract the male adult of fall armyworm moths. The standard bucket trap with a green canopy, yellow funnel, and white bucket has been the most effective trap for capturing the moths of the fall armyworm (Meagher, 2001; Hardke *et al.*, 2015) [47, 81]. Adult moths are often attracted to light sources that emit large amounts of UV radiations, and therefore, light traps may also play crucial role in controlling these pests (Shimoda and Honda, 2013) [63]. Recently, a study in Ethiopia demonstrated efficient control of fall armyworm by using night-time light traps (Gebreziher, 2020) [33].

6.2 Curative methods

6.2.1 Biological Control

Biological control can be defined as the use of living organisms or their components to restrain the density or impact of a specific pest population, keeping its abundance and damage below the threshold level. Being multidisciplinary approach, it employs the knowledge of different fields such as ecology, entomology, weed science, plant pathology, insect pathology and microbiology in effectively solving pest problems in agricultural fields. It is considered as powerful tool and one of the most significant alternative to synthetic insecticides because it is economical, environment friendly, socially acceptable, safe for humans, flora and fauna, self-perpetuating and provide sustainable crop protection. In agricultural system, number of microbial pathogens and arthropod bio-control agents have been successfully used to control plant pests (Pilkington, *et al.*, 2010) [55] and can also provide a viable solution for managing the fall armyworm in the fields.

In bio control of pests, natural enemies of plant pest can play an important role where they are used to control the population of another insect pest (up to 42%) by attacking it to dead. However, the population of natural enemies differ in farmlands depending on whether the farm is sprayed or not as well as the rate and the type of insecticides used. Therefore, the identification of natural enemies of key agricultural pests can offer environmentally safe alternative and can be incorporated into IPM. In case of FAW, broad array of natural enemies such as predators, parasitoids and entomopathogens have been reported for biological control of FAW (Nafiu *et al.*, 2014) [52].

Parasitoids and Predators: Parasitoids are those insects which spend at least one stage of their life cycle in close association with specific life stages of the host pest. For example, they can attack either the eggs or larval stages of the host pest. Thus, the development of the larval stage of the parasitoids results in death of the insect pest. Whereas predators are those which can attack and kill all life stages of the pest but they do not live on the host. Tables 2 and 3 listed the various parasitoids and predators for control of FAW, respectively.

Table 2: Parasitoids in Control of FAW

Parasitoid	Pest Stage	Family	Reference
Trichogramma spp.	Egg	Trichogrammatidae	Tefera *et al.* 2019 [45]
Telenomus remus	Egg	Platygastridae	Tefera *et al.* 2019 [45]
Chelonus curvimaculatus	Egg-larval	Braconidae	Sisay *et al.*, 2018 [82]
Trichogrammatoidea sp.	Egg	Trichogrammatidae	Amadou *et al.*, 2018 [83]
Palexorista zonata	Larval	Tachinidae	Sisay *et al.*, 2018 [82]
Cotesia icipe	Larval	Braconidae	Sisay *et al.*, 2018 [82]
Chelonus insularis	Egg-larval	Braconidae	Meagher *et al*, 2016 [84]
Cotesia marginiventris	Larval	Braconidae	Meagher *et al.*, 2016 [84]
Fly Parasitoids: *Archytas winthemia Lespesia archippivora*	Larval	Tachinidae	Gurrola-Pérez, *et al.* 2018 [25]
Coccygidium luteum	Larval	Braconidae	Otim *et al.*, 2021 [86]
Chelonus Bifoveolatus	Larval	Braconidae	Sisay *et al.*, 2019 [87]
Glyptapanteles creatonoti	Larval	Braconidae	Shylesha, 2018 [65]
Campoletis chlorideae	Larval	Ichneumonidae	Shylesha, 2018 [65]
Forficula sp.	Larval	Forficulidae	Shylesha, 2018 [65]
Ophion flavidus, *Campoletis flavicincta*, and *Pristomerus spinator*	Larval	Ichneumonidae	Molina-Ochoa *et al.*, 2001 [88]
Aleiodes Laphygmae, *Meteorus Laphygmae*, *Meteorus* sp.	Larval	Braconidae	Molina-Ochoa *et al.*, 2001 [88]

Table 3: Predators in Control of FAW (FAO, 2018, Krupnik, 2022)

Predator	Pest Stage	Family
Earwigs: *Doru luteipes* and *Euborellia annulipes*	Egg	Carcinophoridae
Lady bird beetle spp. *Coleomegilla maculate, Cycloneda sanguinea, Hippodamia convergens, Eriopis connexa, Harmonia axyridis* and *Neda conjugata*	Adult / Larvae	Coccinellidae
Calosoma granulatum	Adult/Larvae	Carabidae
Assassin and flower bugs spp. (Zelus, *Podisus*, Nabis, *Geocoris*, Orius and *Anthocoris*).	Larvae	Reduviidae, Pentatomidae, Nabidae, Geocoridae, Anthocoridae
Spiders	Larvae	Araneae
Ant	Larvae / Pupae	Formicideae
Birds	Larvae / Pupae	Anatidae
Trombidium sp.	Larvae	Trombidiidae
Bat	Larvae / Pupae	
Harmonia octomaculata	Larvae	Coccinellidae

Coccinella transversalis	Larvae	Coccinellidae

Entomopathogens

The biological control of FAW with entomopathogens also constitutes a key role in sustainable pest management. Different studies reported the susceptibility of FAW to 16 species of entomopathogens which include fungi, bacteria, viruses, protozoa and nematodes (Agudelo-Silva, 1986; Fuxa, 1982; Gardner and Fuxa, 1980; Molina Ochoa *et al*., 1996; Richter and Fuxa, 1990; Assefa and Ayalew, 2019) [89, 90, 91, 92]. However the incidence and distribution of these natural control agents may vary with their habitat, agricultural practices, geographical location and insecticides use (Fargues and Rodriguez-Rueda, 1980; Miętkiewicz, Dzięgielewska, and Janowicz, 1998; Sosa-Gomez and Moscardi, 1994; Vänninen, 1996) [93-96]. Among the pathogens, different species of *Bacillus thuringiensis*, *Metarhizium anisopliae, Metarhizium rileyi*, *Beauveria bassiana* have been reported to cause significant mortality in FAW populations and help to reduce leaf defoliation in crops (Molina-Ochoa *et al.*, 2003; FAO 2018) [97, 27]. Unlike bacteria and viruses, fungal bio control agents do not need to be ingested and they can invade the host cuticle directly. Thus, the entomopathogenic fungi (Firake and Behere 2020, Raman jam *et al.*, 2020) [29, 60] can infect eggs as well as pupae (non feeding stages) of insect pest. In addition to these pathogens, insecticidal potential of entomopathogenic viruses (Ramanujam *et al.*, 2020) [60] and nematodes (Wattanachaiyingcharoen *et al.*, 2021) [70] have been reported. Table 4 listed the entomopathogens against FAW.

Table 4: Entomopathogens of invasive FAW

Name of the pathogen	Type	Host stage infected	References
Metarhizium rileyi (Farlow) Samson	Entomopathogenic fungus	Larvae	Firake and Behere (2020) [29], Ramanujam *et al.*, 2020 [60]
Beauveria bassiana (Balsamo)	Entomopathogenic fungus	Larvae and pupae	Firake and Behere (2020) [29], Ramanujam *et al.*, 2020 [60]
Spodoptera frugiperda Nuclear Polyhedrosis Virus (Spfr NPV)	Entomopathogenic virus	Larvae and pupae	Firake and Behere (2020) [29], Mehta *et al.*, 2021 [48]
Bacillus sp.	Entomopathogenic bacteria	Larvae	Firake and Behere (2020) [29], Mehta *et al.*, 2021 [48]
Unknown pathogen (like Microsporidian)	Entomopathogenic	Larva	Firake and Behere (2020) [29]
Nomuraea rileyi	Entomopathogenic fungus	Larvae	Mehta *et al.*, 2021 [48]
Steinernema siamkayai and *Heterorhabditis indica*	Entomopathogenic Nematode	Larvae	Wattanachaiyingcharoen *et al.*, 2021 [70]
Steinernema carpocapsae	Entomopathogenic Nematode	Larvae	Molina-Ochoa *et al* 1999 [49]

Botanical Control

Botanical insecticides (plant based) are also another kind of bio control agents which are in use against FAW over the years (Osae *et al*., 2022) [54]. Their use is recommended as a safe, eco-friendly substitute to risky synthetic insecticides, such as organ phosphorus and pyrethroids which lead to ecological and environment disturbances, increase user cost, pest resurgence and insecticide resistance (Arya and Tiwari, 2013) [98]. Farmers in developing countries use these botanicals for centuries to control insect pests of both field crops and stored products because of their affordability and availability (Schmutterer, 1985) [99]. Plants with potential to be used as botanical pesticides are Neem (*Azadirachta indica), Aglaia cordata Hiern*, Custard apple (*Annona mucosa Jacquin*), *Vernonia holosenicea*, long pepper (*Pepper hispidinervum*), *Jatropha gossypifolia*, Castor *(Ricinus communis)*, *Chromolaena chaseae*, *Cedrela salvadorensis*, *Cedrela dugessi*, Chinaberry *(Melia azedarach)*. The efficacy of these plants is most likely due to their secondary metabolites such as isobutyl amides, piperine, and natural lipophylic amides which function as detterants, neurotoxins and anti-feed ants. Examples of some important botanicals are given in table 5.

Table 5: Botanical pesticides against FAW (Source: Bruce *et al.*, 2018)

Plant species	Family	Extract	Mode of Action	References
Neem: *Azadirachta indica*	Meliaceae	Neem oil (0.25%)	Larvicidal with up to 80% mortality in the lab	Tavares *et al.* (2010) [100]
Aglaia cordata Hiern	Meliaceae	Hexane and ethanol extracts of seeds	Larvicidal with up to 100% mortality in the lab	Mikolajczak *et al.* (1989) [101]
Annona mucosa Jacquin	Annonaceae	Ethanolic extract from seeds	Larval growth inhibition	Ansante *et al.* (2015)
Vernonia holosenicea, *Lychnophora ramosissima*, and *Chromolaena chaseae*	Asteraceae	Ethanol extracts from leaves	Ovicidal	Tavares *et al.* (2009) [102]
Cedrela salvadorensis and *Cedrela dugessi*	Meliaceae mortality	Dichloromethane extracts of wood	Insect growth regulating (IGR) and larvicidal with up to 95%	Céspedes *et al.* (2000) [103]
Ricinus communis	Euphorbiaceae	Castor oil and Ricinine (seed extracts)	Growth inhibition and larvicidal	Ramos-López *et al.* (2010) [104]
Jatropha gossypifolia	Euphorbiaceae	Ethanolic extracts of leaves	Antifeedent to larva; synergistic with pesticide	Bullangpoti *et al.* (2012) [105]

Chemical control

Chemical control is another method of pest management (suppression of pest population) and is achieved through the application of synthetic pesticides. In IPM programme, pesticides are the last option of defense against pests when other control methods failed or limited suppression in pest population is achieved. This is because these agrochemicals show quick results either as stomach poison or knockdown and is generally categorized into systemic and contact insecticides. The chemical control of FAW is also achieved through the application of synthetic insecticides of different groups such as methomyl, pyrethroids, cyfluthrin, organophosphates, and methyl parathion (Tumma and Chandrika, 2018; Fotso *et al*., 2019) [69, 31]. In both developed and developing countries. It is generally recommended that an insecticide should be applied when threshold levels of FAW are: if egg masses are found on > 5 percent of the plants and if 25 percent of the plants have leaf damage and live larvae are still present (Bessin,. 2004) [7], if 50 percent of the plants have severe leaf damage (Fotso Kuate *et al.*,2019) [31] and on maize, if 5 percent of seedlings are cut or 20 percent of whorls of small plants (during the first 30 days) are infested, (King and Saunders, 1984) [107]. Unfortunately, due to insufficient or lack of knowledge, farmers does not check the threshold levels for determining the need and dose for chemicals. This raises the concerns that inappropriate use of agrochemicals could lead to resistance development, plant damage, and risk**s** to human health and the environment (Togola *et al*., 2018) [68].

Conclusion

Since the first report of FAW invasion in USA in 1797, this insect has migrated from the America to Africa and then to Asia and Australia so far, over the time period of 227 years and has become the most destructive pest of crops (especially, maize) and has raised alarming situation all over the world. This high rate of invasion of FAW can be related to its high flight capability, lack of diapauses, polyphagy, high ecological adaptation, and high rate of fecundity, wide host range and quick insecticide resistance. Therefore, the control of FAW has become the need of the hour throughout the world to keep a check on its population and to reduce the crop losses. It has become the duty of Government advisories, research institutes and other organizations to make efficient FAW control strategies like IPM. The proper implementation of IPM in FAW management can help to lower down the occurrence and loss from the pest's invasion and thus, can contribute to global stability.

Future Prospects

Along with IPM strategies as summarized in this review, some future studies/technologies are also required to combat with the FAW worldwide. For example, improve monitoring or image recognition by using apps based on deep learning can lead to good performance in monitoring/identifying the invasive pests (Qiao *et al*., 2020; Chiwamba *et al*., 2019a; Chulu *et al*., 2019) [108, 15, 17]. Similarly, based on deep learning, the development of new monitoring techniques can also be developed. A system of automated FAW pheromone trapping has been developed based on machine teaching (Chiwamba *et al*., 2019) [15]. As we know, the FAW outbreaks in different regions of the world occurred at irregular intervals (known as lag-time). Thus, the research on mechanisms of long invasion times can also be exploited to better prevent and control FAW (Huang *et al*., 2019) [109]. Moreover, the rapid resistance of FAW to insecticides can also be slow down by the appropriate use of pesticides at recommended levels, intervals and seasons (Prasanna *et al*., 2018) [57]. Additionally, in recent years, some new techniques have been emerged for controlling pests which include CRISPR / Cas9, RNAi and Nano pesticides. Some scientists are exploring the potential of CRISPR / Cas9 in FAW control programs *viz.* explored the possibility of using the CRISPR / Cas9 system for the modification of the abdominal-A (Sfabd-A) gene, SfABCC2 knockout strain of FAW which is susceptible to cry proteins etc. (Wu *et al*. 2018; Jin *et al*. 2021) [106, 38]. At the last but not the least, the strengthened global collaboration is much needed for biosecurity defenses to prevent insect invasions to protect food security, human health and biodiversity.

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