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The emerging menace of fall armyworm (*Spodoptera frugiperda* JE Smith) in maize: A call for attention and action

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Abstract
The productivity of maize is quite greater than any other important cereal crops but it is still lower than its true yield potential, because of prevalence of many biotic and abiotic stresses. The fall armyworm (*Spodoptera frugiperda* J.E. Smith) having polyphagous nature is an emerging insect which plays a vital role in contributing to low productivity. This particular menace with more than eighty host species causes severe threat to food grains and vegetable crops. A new devastating invasive pest FAW is a major problem for crop production, especially in tropical environment due to its ability of rapid breeding, migration, and feeding habit on a wide variety of hosts. There are several control measures but integrated pest management is widely utilized for managing its infestations. Therefore, in this article, we have highlighted the current situation and control measures of FAW, which could be beneficial to improve its management in corn fields.

Keywords: Maize, management, polyphagous, productivity, *Spodoptera frugiperda*

Introduction
Maize (*Zea mays* L.) is emerging as a vital cereal crop in the agricultural economy as food, feed and raw material for industrial purposes after the most important staple crops like rice and wheat in the entire world and is determined as "Queen of Cereals", due to its high productive potential, easy processing, lesser cost than other food grains (Jaliya *et al*., 2008) [39]. Maize also provides beneficial nutrients for human beings and livestock as well as serves as basic raw material in starch, oil, alcoholic beverages, and fuel production (Punita, 2006) [61]. Recently maize productivity is quite lower than its original potential, attributed to a combination of various bottlenecks in production such as lack of improved and efficient production technologies like insect, pest, disease management practices, moisture stress, low fertility level and poor cultural methodologies (Tufa & Ketema, 2016) [76]. Among many insect pests affecting maize everywhere, a recent invasive and noxious species *i.e. Spodoptera frugiperda*, commonly named as fall armyworm (FAW), is the major pest resulting considerable yield losses of maize today all over the world. FAW, a devouring pest native to tropical and subtropical regions of America where it was first detected in the year of 1797, belongs to family Noctuidae under the order Lepidoptera and was first discovered in the African continent (Goergen *et al*., 2016) [34] in the year of 2016 and has reached China recently, spreading across two continents, west to east, in just three years. Entry of this destructive insect into a portion of Asia is questionable because a majority of people inhabit there and in locations nearby and already a huge pressure is created on food production systems. The occurrence and prevalence of this invasive pest was noticed for the first time by Sharanabasappa *et al.* (2018) [67] from Karnataka, India which is the first reported infestation in Asia, in the month of July in 2018 and subsequently it has spread into other ten states of our country till the middle of March, 2019. Later, its existence was confirmed in the states Maharashtra, Gujarat and Chhattisgarh (Chormule *et al*., 2019; Sisodiya *et al*., 2018; Deole *et al*., 2018) [20, 69, 28]. It is a noxious pest which infests 186 plant species belonging to 42 families among which Poaceae, Fabaceae, Solanaceae, Asteraceae, Rosaceae, Chenopodiaceous, Brassicaceae and Cyperaceae are mostly affected (Casmuz *et al*., 2010) [18]. In our country, its infestation was reported from several crops like maize, sugarcane and sorghum (Sharanbassappa *et al*., 2018) [67]. It results substantial yield loss in maize from 57.6% to 58% (Cruz *et al*., 1999; Chimweta *et al*., 2019) [25, 19]. It extends rapidly from the country West

Africa across the continent, causing severe hazards to several crops (Abrahams *et al*., 2017) [2] and also has spread across Asia subsequently (Kalleshwaraswamy *et al*., 2018) [40]. In its wide native range, FAW is recognized to feed on voraciously more than 350 plant species (Montezano *et al*., 2018) [51] but while considering maize, rice, sorghum and sugarcane it has been noticed that FAW could result in substantial crop losses across the entire planet. FAW is an important pest from economic point of view which attacks maize and various other crops belonging to the family Gramineae (Andrews, 1980) [7]. It is an insect of polyphagous nature having greater than 80 host plant species and causing drastic damage and threat to cereal crops as well as vegetables (Goergen *et al*., 2016; Roger *et al*., 2017; Prassana *et al*., 2018) [34, 63, 59]. Cereals and forage grasses are mostly affected by these caterpillars and are recorded of feeding 186 plant species from 42 families (Casmuz Augusto *et al*., 2010) [18]. Young whorls of leaves, ears and tassels are considered to be the major food causing remarkable damage to maize crop and result in occasional yield loss in totality (De Almeida Sarmento *et al*., 2002) [27]. Both the habit of migration and localized or centralized habit of dispersion are accomplished by FAW moths. The fall armyworm may travel over 500 km or 300 miles before they start oviposition (Prasanna *et al*., 2018) [59]. Aggregations of moths from a single generation can spread rapidly more than 500 km away from the emergence point aided by wind (FAO, 2017; Pogue, 2002) [29, 57] until they are sexually mature and ready to reproduce (Rose, Silversides, & Lindquist, 1975) [64]. FAW comprises two genetic strains like the “rice strain” which prefers rice and other grass species and the “maize strain”, which feeds upon maize most probably and to a lesser extent on sorghum sometimes (Sparks, 1979) [71]. When FAW enters in large number, especially with an intrusive effect, it is forecasted to implement a long lasting and damaging threat to several vital crops, as the surrounding makes adequate preparation for diversified host plant species and favourable weather conditions for reproduction in different areas constantly (Goergen *et al*., 2016; Midega *et al*., 2018; Montezano *et al*., 2018) [34, 47, 51]. It is fortunate that there are so many potential control options which consume very low cost that are built upon local knowledge and ecological or environmental principles available. Those are generally more appropriate to the small and marginal holder farmers who have lack of financial assets to buy chemical insecticides or expensive seed (Abate *et al*., 2000; Altieri and Trujillo, 1987; Grzywacz *et al*., 2014; Orr and Ritchie, 2004; van Huis and Meerman, 1997; Wyckhuys and O'Neil, 2010) [1, 6, 35, 55, 79, 82]. FAW is an insect pest from migratory background and it is known to cause excessive damaging symptoms to corn under the conditions where high temperature and humidity prevail (Ayala, Navarro, & Virla, 2013; Clark *et al*., 2007; Luginbill, 1928b) [10, 21, 43]. FAW is a very devastating and destructive pest of many economically important crops across the globe than any other invasive pest due to their polyphagous nature, rapidly dispersing habit across wide geographical areas and persistence throughout the year. This review article highlights a significant step towards providing knowledge that will enable to identify FAW, and its damage symptoms; understand the life cycle of FAW; and know how to monitor and manage the pest. Accordingly, the main purpose of this review is to provide the status and control measures of this new devastating and challenging insect pest in maize fields across the entire world.

Biology and life cycle

The advancement of harmful populations of pests from economic stand point rely upon several factors like package of management practices, date of sowing, migratory habit, prevalence of different parasites and predators, prevailing weather conditions, and many others. The moths of fall armyworm are very much fascinated to immensely late cultivated maize, which generally can endure significant impairment due to this particular insect. The moths have dark gray coloured, variegated forewings with light and dark blemishes, and an observable white stain close to the farthest end of each. It is sexually more proficient in tropics, where the higher temperature permits more generations in a year in comparison with the temperate regions that may have two or lesser generations per year. In some of the tropical and subtropical tracts of land except areas without frost; FAWs can bring about up to 10 generations in a year (Metcalf, Flint, & Metcalf, 1965) [46]. FAW can be recognised by morphological characteristics or through the injury indications on susceptible crops or molecular delineations like most of the insect pests. Without appropriate accession to advanced apparatus, farmers cannot differentiate among the two strains of FAW. Nevertheless, it should be assumed that the strains belong to the similar species, and the biggest distinction is the host species which are preferred to be feed upon by the different strains. The outer wings of male moths have whitish strips or patches at the lower periphery, while the inner wings are white coloured with dark adornment. The antennae are mostly common to the insects of Noctuids *i.e*. filiform (thread like) antennae. They are usually in an active stage at night like other Noctuids (Oliver and Chapin, 1981) [54]. Fall armyworm completes its lifecycle through four stages such as, eggs, caterpillar (larvae), pupae, and adults (moths) like all other holometabolous. A major attribute of the biology of the insect is that it does not have diapause phase, so various generations can intersect within a single crop cycle when situations are favourable. In reality in many countries, the generations have been constantly ascertained throughout the year, wherever host plants are accessible, in conjunction with many other off-season and irrigated crops (Prasanna *et al.*, 2018) [59]. In such type of regions, development of the population is more hopeful, and the main season crops are more appropriate to be ravaged ahead of time.

Eggs

Eggs are usually laid on the underneath of the leaves, close to the very base of plant, near the convergence of leaf and stem. When insect populations are in high quantity, the eggs may be laid on the higher portion of the plants, on peak of the leaves or upon adjacent vegetative foliage. The eggs are white, pink or light green coloured and circular in shape. Number of eggs per mass fluctuates significantly but commonly range between 100 and 200. Total average egg production per female in her lifetime is almost 1,500, with the highest number of about 2,000. The female FAW also makes a deposition of a coating of scales between the eggs and over the egg masses and the extent of the length of this state is merely two to three days during warm circumstances. Tropical rains are very much beneficial in demolishing the lifecycle of this pest by cleansing off the eggs from leaf surface on the ground where predators can feed them, or if they are managed to be hatched, they are not a food source.

Larvae
Larvae come forth concurrently three to five days after oviposition, and immigrate to the leaf whorl. The rate of fatality following appearance may be higher in some conditions due to different climatic influences and aggression by pathogens, predators as well as parasites. There are six larval instar stages and while considering the second and third instar phases, larvae are mainly cannibalistic, causing presence of only one larva in whorl. Young larvae are green in colour, having a black head, which alters into an orange colour in second instar state. Ballooning is often noticed and larvae are blown away by wind to other plants which results in 100% infestation sometimes. The well developed mature larvae are 30 to 40 mm in length and differ in colour from light tan to green and black also. The face of the matured larva is pronounced with a light coloured inverted "Y". The maturation time of larvae ranges within 14 to 22 days, after which they fall on the ground surface for pupation. The absence of diapause phase is a chief operator comprising at least 12 intersecting generations in a year which makes FAW an important pest both during the rainfed and irrigated cropping seasons.

Pupae
Pupae are reddish brown in colour and may be difficult to search for a common farmer. The phase of pupation in general occurs in soil, at a depth of 2 to 8 cm. The larva fabricates a loose cocoon which is oval in shape and 20 to 30 mm in length. When the soil is too stiff, larvae may entangle leaf detritus and other materials altogether for formation of a cocoon on the surface of soil. In some cases, the pupae may also be detected in maize cob. The duration of this particular stage is almost eight to nine days during summer, but reaches it takes 20 to 30 days during winter.

Adult
Adult moths are 20 to 25 mm in length; with a wing spread of 30 to 40 mm. Adults pose nocturnal habit and are the most dynamic and alive during warm and humid evening. The male forewing is variegated with light brown, grey and straw colour while the female has light coloured forewing. The dark grey coloured moths of FAW makes them burdensome to notice, more specifically when relaxing near or on the ground surface, but in some instances while the population is quite more in number, the cultivators may spot some of the adult insects in their field. Following a pre-oviposition time period of three to four days, the female naturally lays her eggs mostly during first four to five days of life cycle, but some oviposition proceeds to happen for up to three weeks. The continuation of adult phase is approximated to about 10 days, ranging between 7 to 21 days.

FAW's economic importance and host plants
Economic importance: Fall armyworm is genuinely a caterpillar; it is not a "worm" in true sense. It is exceptionally detrimental pest of cereal crops and many other cultivated plants in farmer's field. FAW jeopardizes the food and nutritional security of millions and millions of farming dependent families. If they are mismanaged or unmanaged or there is an absence of natural biological control methods, FAWs can result in severe yield losses in corn and other crops also. In a broad sense, the response of the crops to the infestation mainly depends on the pest population level and the infestation time, presence of natural foes and pathogens that can aid to maintain the population levels, the health condition as well as vigour of the maize. It is suggested by the expansive range of host species, comprising advantageous crops from export point of view that FAW is hopefully spreading to Europe and Asia, and as a vital quarantine pest, can conceivably curb the trade and export, considerably affecting the economy of different countries. Necessary and emergency acknowledgement has been relied upon the synthetic or chemical pesticide usage. The acquisition and allocation of very toxic/hazardous pesticides worth millions of dollars, as a portion of the quick response to FAW infestation, is not only unsustainable after all, but also is confined to be highly devastating to human health conditions, biodiversity and environment, and will cause an unendurable "pesticide treadmill". Accordingly, it is exceedingly influential to demoralize the application of dangerous pesticides against fall armyworm, and as a substitute to eagerly elevate and arrange confirmed, sustainable and accessible technologies, as part of an integrated pest management package of practices.

Host plants of FAW
Fall armyworm apparently exhibits an ample range of host species, with beyond 100 documented hosts belonging to 27 families. The insect chooses Graminaceous plants mainly along with maize, field corn, sweet corn, millets, sorghum, rice, wheat and sugarcane. The destructive symptoms of insect's feeding are additionally detected on many other agricultural crops, like cowpea, groundnut, potato, soybean and cotton. Other host species involve barley, Bermuda grass, clover, oat, ryegrass, sugar beet, Sudan grass, and tobacco as well as apple, grape, orange, papaya, peach, strawberry and a number of flowers are also often harmed. While the larvae are innumerable, they defoliate the favoured plants, achieve an "armyworm" habit and disseminate in massive numbers, devouring almost all vegetation in path. Field crops are very often damaged, including alfalfa, barley, Bermuda grass, buckwheat, cotton, clover, corn, oat, millet, peanut, rice, ryegrass, sorghum, sugarbeet, Sudan grass, soybean, sugarcane, timothy, tobacco, and wheat. Among vegetables, only sweet corn is frequently hampered, but other crops are attacked occasionally. Weed species are also recognized to serve as host plants that involve bent grass (*Agrostis* sp.) crabgrass (*Digitaria* spp.), Johnson grass (*Sorghum halepense*), morning glory (*Ipomoea* spp.), nutsedge (*Cyperus* spp.), pigweed (*Amaranthus* spp.) and sandspur (*Cenchrus tribuloides*).

Critical crop stages of maize for FAW attack
The growth, development and yield of maize rely upon the existing environmental situations. A land cultivator can advance the natural circumstances by utilizing well developed high quality cultivars, tillage, and time of sowing, water, and nutrient as well as pest management, to improve the crop health and obtain optimum yield levels. Maize normally passes through different growth stages which are divided into vegetative stage and reproductive stage. For this reason, assuring a healthful and vigorous or efficacious crop by timely sowing, rapidly maturing varieties, use of good quality seeds and excellent utilization of manures and inorganic or chemical fertilizers and will guarantee that corn is in greater health condition and can evade or combat the infestation or recover from the attack. Fall armyworm infests maize from vegetative to tasseling and ear formation stage also. Delayed

cultivated crops and late maturing hybrids are more favourable to be infected. When the pest can adversely affect maize in almost all developmental stages, FAW centralizes on late planted crops that have not still born silk. It can be efficaciously managed while the larvae are tiny *i.e.* before third instar stage. It is more difficult and costly to control bigger larvae of fourth to sixth instars, customarily after they are hidden under the excrement of insect larvae. When tassels appear from the whorl, it push out the larvae, momentarily susceptible to natural enemies, sun exposure and low-risk commodities. Until ears are obtainable, large larvae will search for other areas to hide during daytime *e.g.* in leaf axils. Larvae are pushed from maize ears, and if new larvae from eggs are dropped on plants, will rapidly proceed to the advancing ears. Small larvae generally come into the ears through the channel of silk, but bigger larvae feed upon through the husk, into the underneath of ear through the guarded region around the ear shank, to immediately feed on maturing kernels. Distinguishing those critical stages of FAW susceptibility is critical for obtaining management practices against the harmful pest.

Symptoms of FAW damage

The larvae are fond of feeding on corn, but have also been documented to exfoliate other crops, involving millets, sorghum, barley, rice, wheat, sugar cane, wild grasses and vegetable crops. The insect can hamper the crop at different growth and developmental stages, from early vegetative up to physiological maturity. FAW can devour young plants of maize, thereby resulting in the need for resowing, and it also damages leaves and provides them a ragged and torn appearance, hence interrupt the grain filling capability. Leaf exfoliation causes severe "window paning" which is the most familiar impairment evidence; nevertheless, this symptom is often imperceptible or indistinguishable from the affected areas because of other stem borers. Generally a lot of young larvae can be present on similar plant, but usually one to two older larvae may be observed on a single plant, because others immigrate and feed upon plants present in neighbours. It is not exceptional to get one larva feeding upon another larva of same species, and they do not also make hesitation to assail larvae of other species. Afterward larval instars chew bigger holes, cause torn leaves, and create larval droppings like sawdust, but fresh feeding produces massive lumps. Severely infected crop fields look like they are hit by a drastic hailstorm. During daytime, caterpillars conceal deep into the leaf whorls and devastate developing silks and tassels, thus restricting fertilization. Fall armyworm also interferes with pollination and injury to the cobs may direct towards fungal infection, Aflatoxins production, and loss of grain quality. It may feed on developing kernels; thereby reduce productivity, expose maize cobs to secondary infestation and loss of grain quality as well as quantity. In corm, they defoliate and kill young plants, result in huge loss of yield, and feeding of ears may cause depletion in grain quality and yield (Capinera *et al*., 2017) [17]. Continuous abundance or fecundity of this pest at superior environmental situation is foreseen to create a drastic threat to the crops (Goergen *et al*., 2016) [34]. Both the vegetative as well as reproductive organs are eaten voraciously by the FAW larvae. Young larvae mostly prefer epidermal leaf tissues and make cavity in leaves, and it is the exclusive symptom of destruction. Dead heart is also a reported sign constituted by the insect feeding on young plants through the leaf whorls. The matured larvae usually remain in the whorls of older plants and they can feed on maize cob or kernels also, decreasing grain yield and quality (Abrahams *et al*., 2017; Capinera *et al*., 2017) [2, 17]. Significant impairment to maize crop is established by larvae after feeding upon young leaf whorls, ears, silks and tassel which occasionally directs to severe yield loss (De Almeida Sarmento *et al*., 2002) [27]. The fall armyworm results massive destruction or damage to maize and loss of yield has been reported to be more than 70% (Hruska and Gould, 1997) [37]. Identifying infestations of FAW before it can cause damage from economic point of view is the key of its treatment. If infections are recognized too late, the effects of injury are mostly unalterable (Rwomushana *et al*., 2018; Capinera *et al*., 2017) [65, 17].

Overview of different approaches to pest management

If 5% of seedlings are devoured or 20% of whorls of maize plants during the first 30 days are infected by fall armyworm, it is approved to make an application of an efficacious management practice to impede further destruction (Fernández, 2002) [31]. The appropriate time for administering various control measures is so much important for efficient pest control, also considering the larval cycle of FAW and the time of the day for employment. In various countries, feedbacks of farmers are principally dependent upon the utilization of chemical pesticides. Such a package of practices should involve impressive monitoring, scouting and surveillance; timely and need oriented implementation of environmentally sustainable and low risk associated synthetic pesticides; preservation of indigenous natural enemies and traditional biological control methods; deployment of varieties with higher degree of resistance; encouragement of low expense agronomic or cultural practices; and habitat management strategies *etc*. The direct activities that can be obtained to control fall armyworm are chiefly up to individual peasant in fields. For this reason, the farmers demand the proper guidance, implements and resources to considerably administer the pest. Therefore, the management approaches are need to be integrated into an expansive pest control aspect, along with a concentration on interventions that can bring about pest governance advantages throughout a vast array of pests and that are well adapted to diversified crops and cropping patterns.

Agro-ecological control of FAW

Agro-ecological administration is an influential ingredient of a pest management approach for fall armyworm. Since the dawn of agriculture, cultivators have accomplished pest control services of the organisms inhabiting in and around the boundary of the fields. Agro-ecological approaches are dependent on three complementary methods: (i) Sustainable or eco-friendly management of soil fertility, which ameliorates health and pest resistance of crops (Altieri and Nicholls, 2003) [4]; (ii) Advancement of biodiversity at a wide range of spatial scales from field up to the landscape and hence contributing living space for natural enemies (Altieri and Letourneau, 1982; Bàrberi *et al*., 2010; Landis *et al*., 2000; Murrell, 2017, Nicholls and Altieri, 2004) [5, 11, 42, 52, 53]; and (iii) Definite control measures purposed to inhibit outburst of the pest or decline their adverse effect. Innumerable interventions are previously adjusted with other conception of sustainable management of land, like climate smart agriculture. For instance, different steps involve crop rotation, intercropping and mulching at field level; admitting distinct crop margins and in field variations (Tschumi *et al*., 2016) [75], planting shrubs and trees, and accepting few regions to reconstruct genuinely (Pumariño *et al*., 2015) [60] at farm scale; and amplifying the quantity and diversification of forest coverage and the areas dominated by various agricultural crops at the landscape level (Gurr *et al*., 2003; Landis *et al*., 2000; Murrell, 2017; Veres *et al*., 2013) [36, 42, 52, 81]. Diversity is an elementary constituent, as several natural enemies may be more powerful in managing various pests at different developmental or growth stages or may be in different seasons. Investigations have displayed that the consequence of diverseness in the transmission of ecosystem services, involving pest management practices, is improved as environmental heterogeneity through spatial and temporal dimensions increases (Tylianakis *et al*., 2008) [77], and seasonal climates with greater inter annual rainfall deviation generate extremely diversified situations for cultivators of farmers above the distribution invaded by fall armyworm. An agro-ecological technique integrates the combination of complementary interventions, throughout a wide range of geographical scales, into farming system. Mostly the adopted measures are multi-functional, such as those providing to amended soil fertility or diverse farm produce. Therefore, the strategies exploit natural synergies within farming systems. Contributing smallholder farmers the basketful opportunities will be very much fundamental for up scaling agro-ecological approaches of pest management (Coe *et al*., 2014) [22]. Nevertheless, it is also vital to detect optimum negative or adverse effects of interventions and lastly, it is crucial to deliberate the functions of agro-dealers, who generally pose a major responsibility in providing inputs, *e.g.* seeds or seedlings for intercrops and boundary plants, but through the existing marketing channels may be further disposed to encourage the indiscriminate usage of dangerous, harmful, broad-spectrum chemical or synthetic pesticides.

Agro-ecological approaches to pest management:

(1) Minimum soil disturbance improves soil biological properties, hence amending better soil nutrient management; (2) Mulching with different crop debris defends the soil exterior portion and augments organic carbon to restore soil fertility, and in addition provides better dwelling place for predators more specifically spiders, earwigs, beetles and ants *etc*; (3) Planting leguminous crops as intercrop or cover crop also improves soil fertility through nitrogen fixation, alters the environmental conditions in field for beneficial insects, involving parasites and predators; (4) Shrubs/trees carrying flowers or extra flora nectaries nurture communities of ants and small wasps; (5) Boundary trees *e.g.* fodder, fuel wood, shelter providing trees allow perches and roosts for birds and bats and improve the structural diversity of farm habitat through shade and shelter; (6) Crop rotation also augments soil fertility or soil health and improves the farm environment with diversification; (7) Steady and routine scouting by farmers to detect harmful pests and estimate the threat authorizes management decisions; (8) Weeds are permitted to flourish between maize rows and along the field boundary can provide suitable environment for predators and boost parasitoids and predatory wasps through the arrangement of nectar; (9) Insectivorous birds and bats provide a vital role in depleting pest abundance in distinct agro-ecological conditions; (10) Appropriate nest provision for predatory wasps or ants could be utilized to intensify the abundance of insect predators

Biological control

Biological control measures can be recognized as influential tools which provide environmentally reliable and sustainable safeguard options. The achievement of these methods trusts upon the apprehension of the acclimatization and establishment of suitable control agents in agro-ecosystems. Microbial formulation based pathogens and arthropod bio-control agents have been profitably utilized in agricultural systems (Pilkington, Messelink, van Lenteren, & Le Mottee, 2010) [56] and their production costs have also been remarkably reduced recently because these are mainly mass produced in liquid medium (Mahmoud, 2016) [44]. A large number of parasitoids, predators as well as pathogenic organisms are beneficially attacked by larval and adult stages of fall armyworm but biological control methods cannot substitute the traditional insecticides. The nomadic performance of the insect makes the natural enemies less active. Several insect species have been recorded to parasitize larvae and eggs of FAW. Ashley (1979) [9] listed 53 different species of parasitoids which are generally brought up from FAW eggs and larvae. Those comprised *Apanteles marginiventris*, *Campoletis grioti*, *Chelonus insularis*, *Meteorus autographae*, *Ophion* spp., *Rogus laphygmae*, *Ternelucha* spp. and *Eiphosoma vitticole*. The vertebrate predators such as birds, skunks and rodents also feed upon larvae and pupae of fall armyworm (Capinera, 2000) [16]. The pest is recognized to be vulnerable to at least 16 species of entomopathogens involving viruses, fungi, protozoa, bacteria, and nematodes (Agudelo-Silva, 1986; Fuxa, 1982; Gardner & Fuxa, 1980; Molina Ochoa *et al*., 1996; Richter & Fuxa, 1990) [3, 32, 33, 49, 62], but their presence and prevalence may differ with their dwelling place. Additionally, geographical location, agricultural management practices, and use of insecticides have an impression on the appearance of natural control operators that feasibly assist to govern FAW communities (Fargues & Rodriguez-Rueda, 1980; Miętkiewicz, Dzięgielewska, & Janowicz, 1998; Sosa-Gomez & Moscardi, 1994; Vänninen, 1996) [30, 48, 70, 80]. The noted pathogens like *Bacillus thuringiensis*, *Metarhizium anisopliae* and *Beauveria bassiana* can result in considerable mortality and aid to diminish leaf exfoliation in field crops (Molina- Ochoa *et al*., 2003) [50]. Viruses have been also demonstrated to pose confined efficiency against FAW, which is not temporarily efficacious, approving substantial injury prior to insect fatality (Sparks, 1986) [72].

To better have an idea about natural enemies, it is very much essential to distinguish between “natural” and “applied” biological control (bio-control). Natural bio-control is the abatement of a pest population through the use of natural enemies, without human interference; while applied biological control is the depletion of the communities of a pest by natural enemies administered by mankind and both these types are equally significant and acceptable. Three different forms of biological control measures are usually identified, depending upon the process by which natural enemies are regulated. In case of “classical bio-control” approach, exotic or foreign natural enemies are imported and released in the regions infested with the insect pest. Alternative way for improving the efficacy of bio-control is to implement the technologies designed at increasing the population of endemic natural enemies. This is accomplished by the occasional discharge of huge numbers of natural enemies in the field condition which is entitled as “inundative” bio-control. Correspondingly, the intention is to augment attempts that progressively increment the community of natural enemies, known as "augmentative bio-control". A third form of biological control method is through the "preservation" of natural enemies and, in comparison to the first two forms it performs with the existing natural enemies in an indirect manner, creating the environmental situation more favourable for them. The insects that are distinguished as bio-control agents are classified as either "parasitoids" or "predators." Parasitoids are important bio-control agents of which at least one of their life stages is accomplished in the pest. Predators, on the other hand, just prey or hunt on the pest in most susceptible stages, such as eggs or larvae. There are also pathogens, which infest the larvae and result in mortality in many conditions. Many parasitoids are found that parasitize the eggs, larva and pupal stages and others parasitize during multiple stages of life cycle. The parasites dispose eggs inside the body of fall armyworm and hinder the further enlargement of the host to become an adult. The following sections will be helpful as it provides some examples of parasitoids and predators of fall armyworm that might be confronted, and discusses the methods by which the farmers are able to identify them.

Parasitoids

Trichogramma: They are very tiny insects; the female lays eggs within the eggs deposited by fall armyworm. Within a very few hours *Trichogramma* larvae starts to defoliate the eggs of FAW. The parasites consummate its entire lifecycle inside FAW eggs and following the appearance of it; the cultivators may notice egg masses on leaves, with very minute ruptures from which *Trichogramma* came forth. Very soon after originating, it instantly starts the procedure of finding new egg masses to carry on multiplication.

***Telenomus*:** *Telenomus* is bigger than *Trichogramma* and has a black, glossy body. After the entire enlargement of the immature stage of this parasite, the adult penetrates through a tiny hole made in the eggs of FAW, through which it arises. After completion of emergence, the peasants may discover *Telenomus* meandering around the egg masses from which they came forth or they may fly away to hunt other invaded masses.

Chelonus: The female *Chelonus* lays eggs inside the eggs of fall armyworm, but unlike *Trichogramma* and *Telenomus*, the invaded FAW eggs hatch to larval phase and will carry it inside the parasite. Within a very brief period, the larva which is parasitized steadily curtails down its feeding, until its death happens. While the parasite's development is completed, the caterpillar of fall armyworm abandons the plant, proceeds into the soil, and immediately weaves an apartment or cocoon to become a pupa, and within few hours it transforms into pupa, and thereafter into an adult.

Campoletis: The females oviposit eggs inside the first and second instars of fall armyworm and the larva finishes its whole cycle feeding upon the internal contents of the pest. The caterpillar alters its performance and the FAW larva leaves the whorl when the larval stage of the parasite moves towards the fifth instar; then approaches the higher leaves, living in that place until its death. Parasitizing small sized caterpillars, including death of the host species, the parasite extremely decreases the consumption of the leaves; thereby diminishing the injury in the field.

Cotesia: They are very tiny wasps; adults deposit many eggs and the parasite's larva arises as well as feeds within the body tissue of fall armyworm after three days. The parasitoid larvae weave a cocoon like apartment or chamber on the leaf and transform into a pupa soon after leaving the host species, and hatches within a week. *Cotesia* is chiefly endoparasitoids, and are better antagonist than *Chelonus insularis*.

b. Predators

Ladybird beetles: Adults of different size and colour can feed voraciously upon eggs and young larvae of fall armyworm. Usually, the larvae of the predators become a pupa within the plant, and pollen as well as fungal spores are much more vital components of their diet. Ladybird beetles are competent predators in the larval and adult stages as well. Farmers can conserve the beetles by using fewer pesticides in their fields.

Earwigs: Earwigs have long mandibles or mouthparts; well organised compound eyes; long, filiform and multiple segmented antennae and these insects are major natural enemies for fall armyworm as their body structure enables them to perforate into the hiding places of FAW like leaf whorls or ears. They are naturally observed in huge quantity on the plant as they demonstrate affectionate concern in the security of hatched eggs and nymphs.

Predatory bugs: Predatory bugs can feed on fall armyworm; have high searching or piercing efficacy; have a capability to increase population and aggregate rapidly when there is bountiful prey. Additionally it can also survive in low prey density that makes them more impressive. They can make puncture in the larvae of FAW; inject a toxin like substance that results in paralysis in a comparatively shortest time span; then kill the larva when its internal fluids are sucked out by the predator species. We should not be presuming that any bug noticed on the plant is a predator. Farmers can implement different management options like sugar solutions which can act as food source for predatory bugs to enhance their activity in field conditions.

Soil surface beetles and ants: Those black or brown coloured beetles dwell on the soil surface and are naturally nocturnal in habit. They are fundamentally carnivores, and can devour on larvae of fall armyworm when they drop down to the soil for pupation.

Pathogens

The larvae of fall armyworm can be damages by a large numbers of pathogens, which can cause fatality or mortality in few circumstances. The pathogens involve viruses like *Spodoptera frugiperda* granulovirus and *Spodoptera frugiperda* multiple NPV, which can be developed into commercial commodities for vast field scale application. Once infested, the virus expands to the full body of the insect. Invaded caterpillars can demolish slighter than 10% of the food generally devoured by a healthful caterpillar. The dead larvae may break down and produce liquids or fluids, when consumed by other larvae spread the infection. Other pathogens like entomopathogenic fungi infest the larva of fall armyworm through the body and kill the pest by destructing tissues and producing toxins. Infected insects cease feeding, change colour, and ultimately die. The most common genera are *Beauveria* and *Metarhizium.* There are also few bacteria which have been developed into bio-pesticides like *Bt* commercially and can result in death of fall armyworm. We have found some evidences that the larvae of FAW are also be damaged by entomopathogenic nematodes. Farmers should search for dead or infected larvae in their cultivated lands to apprehend the responsibility of pathogens in fall armyworm control.

Botanical control

The botanical pesticides are approved as an alternative to precarious synthetic pesticides or insecticides, *e.g.* pyrethroids and organophosphorus compounds which may cause interferences in the environmental conditions, increase cost, pest resurgence and resistance to different insecticides (Arya & Tiwari, 2013) [8]. Due to the affordability and accessibility of botanical insecticides, cultivators of developing countries generally use those safer and more eco-friendly and sustainable tools for past centuries to manage insect pests of both the field crops as well as stored commodities (Schmutterer, 1985) [66]. Extracts of plants including *Azadirachta indica*, *Milletia ferruginea*, *Croton macrostachyus*, *Phytolacea docendra*, *Jatropha curcas*, *Nicotina tabacum* and *Chrysanthemum cinerariifollium* have been utilized with a great success for controlling such type of insect pests (Schmutterer, 1985) [66]. It was reported by Silva *et al*. (2015) [68] that high fatality of fall armyworm larvae can be achieved by using seed cake extract of *A. indica*. Recently in a study carried out by Martínez *et al*., 2017 [45], they have observed that the ethanolic extract of *Argemone ochroleuca* from Papaveraceae family caused larval mortality of FAW due to a depletion in feeding habit and retarded larval growth. Extracts of several plants display insecticidal efficiency against FAW (Batista-Pereira *et al*., 2006) [12], but comparatively some have been successfully commercialized in the market. Azadirachtin obtained from neem and pyrethrins achieved from pyrethrum are the most widely accepted products; while some other products are based on rotenone, garlic, nicotine, rianodine, quassia and are registered throughout the entire world (Isman, 1997) [38]. These commercialised products may be diluted with application of water and sprayed in similar method as the chemical pesticides are applied in the fields, although dust formulations are also available in the market easily. While considering the neem based products, the great problem is the high photosensitivity of azadirachtin, which dissociates due to sunlight exposure; thereby, neem has a lower residual life under field situations.

Chemical control

Chemical control is usually obtained due to the deployment of synthetic or chemical insecticides (Blanco *et al*., 2014, 2010; Hruska & Gould, 1997) [13, 14, 37], but it involves high cost, drastic environmental contamination, resistance to chemicals, and pest resurgence (Colborn, 1995; Crowe & Booty, 1995) [23, 24]. The appropriate timing for chemical application is very much vital for efficient pest management and the life cycle of the pest as well as the time of day are crucial. Spraying will be ineffective when larvae are deeply embedded inside the leaf whorls and ears of maize and during the daytime because larvae only come to feed upon plants at night, dawn or dusk (Day *et al*., 2017) [26]. Threshold levels are not being utilized significantly in determination of the demand for chemical application; hence inappropriate use of chemicals can obviously lead to resistance and resurgence development, plant injury, and damage to human health and our surrounding environment (Togola *et al*., 2018) [74]. The use of chlorantraniliprole and cyantraniliprole as seed treatments declined the need for foliar sprays against fall armyworm in soya (Thrash *et al*., 2013) [73]. Thiodicarb and clothianidin diminished the number of plants invaded by FAW larvae, but chlorpyrifos, fipronil and thiamethoxam (Camillo, Di Oliveira, de Bueno, & Bueno, 2005) [15] and kerosene (Portillo, Meckenstock, & Gómez, 1994) [58] were not effective significantly. Another major strategy is to go for application of insecticide to the soil at the time of sowing, although it is feasible to be less efficacious than seed treatments. Dry mixtures of sand with trichlorfon which are formulated as granules or powder and applied into the whorls with a plastic bottle are recognized to be more efficient and broadly used by the smallholder cultivators (Kumela *et al*., 2019) [41], while the mixtures of chlorpyrifos with sawdust declined the quantity of pesticide required by 20%, without any loss (Van Huis, 1981) [78].

Surveillance, monitoring and scouting

Monitoring, surveillance and scouting are essential for rapid identification of the prevalence of fall armyworm and to safe guard against yield losses while maintaining preservation of various ecosystem services effectively and economically and minimizing hazards to the environmental situation. Surveillance should be done throughout the whole year as various generations appear which affect maize plants at various growth and developmental stages and also other host plants are attacked by them regularly. Irrigated areas become the reservoirs of host species especially during the dry season, from which immigration tends to occur quickly at the onset of the monsoon season. Monitoring and managing the FAW populations on off-season crops may be crucial in depleting the infestation or infection in rainfed crops mainly.

Surveillance is an informal and passive identification of pests in a specified region, chiefly carried out at farm level. Farmers are the first to detect emergent obstacles. The collective response of millions of peasants can supply powerful information about the pest infestation dynamics in a region.

Monitoring indicates the active tracking of the presence and prevalence of FAW population and movement inside a recognized area or region. It may happen at different levels like community, district, country or regional level, most probably facilitated by the Governments, and trained technical personnel who systematically collect information to notify policymakers and practitioners about the presence and severity of the pest worldwide.

Scouting is the utilization of science oriented protocols by trained individuals or extension workers or farmers to notice the pest in their cultivated lands. It allows the farmers to assess the pressure or intensity of the pest and also the crop's performance in the field. Scouting is typically carried out in order to evaluate the economic risks associated to the pest infestation as well as the potential efficiency of pest management interventions. Early recognition of fall armyworm infection requires timely and regular scouting. Appropriate time management may be obtained by the use of pheromone traps in the fields before sowing or planting throughout the entire growing season, in order to trap male moths; and the catches are recorded on weekly basis.

Conclusion

Fall armyworm (FAW), a voracious annoyance to the agricultural crops was originated in North and South America and has subsequently expanded throughout the continent and moved across Asia. Favourable environmental conditions for the pest can aid them to rapidly multiply and extend into many more regions. It has been anticipated that it could create substantial crop losses all through the world; hence endangering the subsistence of millions of resource poor peasants. In their hastiness to reciprocate to fall armyworm, Government is promoting indiscriminate usage of harmful chemical pesticides or insecticides which not only are creating risks to human health and environment, but also can threaten smallholder's pest control approaches that rely upon a greater range of natural enemies. Agro-ecological strategies propose culturally suitable very low cost pest management practices that can be eagerly amalgamated into the current achievements to ameliorate incomes of smallholder farmers and elasticity or resilience through sustainable intensification. Such type of strategies should be encouraged as a central ingredient of integrated pest management (IPM) programmes in conjunction with breeding of crops for developing pest resistance power, classical biological management and proper selective utilization of safe pesticides. Notwithstanding, the applicability of various control measures for diminishing FAW densities and adverse effects need to be deliberately appraised throughout diverse environmental condition and socio-economic situation before they can be suggested for wide scale application. For assisting this procedure, we have analysed various evidences for the effectiveness of potential methods for managing FAW population, considering the allied risks and dangers, and have depicted awareness to crucial knowledge gaps. Nonetheless, we are approving the embedding experiments into up scaling programmes so that the cost and benefit of those interventions may be ascertained throughout the divergent biophysical as well as socio-economic backgrounds that are noticed in the infested range. Additionally, we are facing a burning desire to amplify attention and awareness among farming communities regarding the life cycle of FAW, inspection of the pest and also its natural enemies, better having knowledge about the appropriate stages of crops on which higher economical damage may happen, and also the right time of involving management approaches, implementation of comparatively low-cost agronomic package of practices and other landscape management options for sustainable management of this particular pest. At the similar time, it is very much significant to acquaint, authenticate, and deploy low cost, environmentally sustainable, and efficacious technological interventions over the short, medium and long term management options for suitable control of FAW, more specifically keeping in view that a substantial majority of the farmers are low resource smallholders.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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