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Invasion, economics and management of fall armyworm in SAARC nations: A critical review

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Abstract

Fall armyworm (FAW) is an invasive transboundary insect pest that feeds on more than eighty different plant species. It is especially devastating to grain crops like maize and sorghum. Ecological success of FAW relies on its versatility and capacity to adapt to a wide range of climatic situations. In warm and muggy climates, females can lay up to two thousand eggs, which will hatch into voracious larvae which consume large amounts of plant tissue. It is well-documented that this insect can travel great distances when aided by winds and weather. From the Americas through Africa, Asia, and beyond, this pest was spotted in India in May 2018, and has expanded to other South Asian Association for Regional Cooperation (SAARC) countries like Bangladesh, Nepal, Bhutan, Sri Lanka, Afghanistan, and Pakistan, and may go further. Temperature fluctuations in SAARC nations allow FAW to cause more damage to maize in the summer (Kharif) than in the winter (Rabi), while sugarcane, rice and sorghum are less susceptible to its infestation. Global trade, transboundary transit, and natural dispersal mechanisms like migration all contribute to the spread and invasion of the pest. A successful integrated pest management plan for FAW should include the strategic deployment of resistant cultivars, crop rotation, pheromone traps, natural enemies of predators and parasitoids, entomopathogens, and bio- and synthetic pesticides. Only educating farmers on the biology and ecology of this pest and training them on how to optimize integrated management approaches would ascertain sustainable FAW management in SAARC nations.

Keywords: Fall armyworm, SAARC, Natural enemies, Biopesticides, Economics

1. Introduction

Pest and disease-related reductions in maize yield are a major worry everywhere, particularly in areas where maize is a significant staple crop. Stem borers, fall armyworms, and maize weevils are a few of the destructive pests that have an impact on maize production worldwide. International Maize and Wheat Improvement Center (CIMMYT) has estimated that pest infestation can result in up to 30% yield declines worldwide in the production of maize [1].

In many regions of the globe, including South Asia, maize crops are confronting the severe attack of the emerging invasive pest fall armyworm, Fall armyworm (FAW) (*Spodoptera frugiperda* J. E. Smith). South Asian Association for Regional Cooperation (SAARC) nations are located in the southern part of the Asian continent and consist of eight countries: Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, and Sri Lanka.

The Food and Agriculture Organization (FAO) estimates that South Asian SAARC nations produced approximately 29.9 million tonnes of corn overall in 2020, with an average yield of 3.8 tonnes per hectare [1]. With the introduction of invasive fall armyworms in SAARC nations in 2018, the productivity of maize is in jeopardy [2]. The yield loss brought on by this invasive pest can change based on the extent of the infestation, as well as other elements like the weather and control techniques.

According to the severity of FAW infestation and the management techniques employed, the yield loss in maize could range from 20% to 70% in South Asia [1]. However, based on a number of variables like climate, soil, management techniques, and pest pressure, maize yields can vary considerably.

The FAW is an economically important Lepidopteran Noctuid pest native to tropical and subtropical regions of the Americas. It later spread to other parts of the world, including Africa, Europe, and Asia [3,4]. In the 19th century, FAW was spread in devastating form and caused an epidemic in America [4].

As far as the nature of FAW is concerned, it is polyphagous and can be found to infest a wide range of host crops. A total of 353 plant species of 76 families were documented to be infested by FAW, most of which were in the Poaceae family (106), Asteraceae family (31), and Fabaceae family (31 species) [5]. Having spread from America to West Africa in 2016, the pest has reached more than 40 countries in just three years [4].

According to estimates, the fall armyworm alone reduces corn yields in sub-Saharan Africa by up to 8.3 million tonnes annually [1]. In May 2018, FAW was first identified in Asia from Karnataka, India. Thereafter, it spread to China in 2019 and some SAARC countries of South Asia to South East Asia in 2020 [4,6].

Researchers showed that African and Indian strains of FAW were genetically indistinguishable [6]. The pest has been documented to mostly affect the maize crops grown in warmer regions of America, Africa and Asia. It is assumed that intercontinental trade helped FAW arrive in the Asian regions.

A temperature of 17-35°C and 0-400 mm annual rainfall is the most suitable condition for FAW which generally stays in tropical warm climate regions. Less than 10°C, this pest is unable to survive and move from a cooler region to a warmer region [7,8]. Therefore, inherent tropical and subtropical climates of SAARC countries, with their year-round wet, humid, and semi-arid conditions, are ideal for reproduction, infestation and spread of the invasive pest. The region is well known for its agricultural diversity as a wide variety of crops and farming practices are widely used.

Common cereals farmed in the area include rice, wheat, maize, sorghum, and millet, all of which are vulnerable to various pests and diseases. In recent years, fall armyworm infestations have wreaked havoc on maize, the world's third most widely cultivated crop after rice and wheat, while sparingly damaging sorghum, rice, sugarcane, and cabbage in South Asia [9,10].

This pest can infest a wide variety of hosts and can spread to new areas far from its original hotspot. Thus, the economic impact of FAW infestations prompted us to conduct a comprehensive review analysis of its ecology, biology, economics, and management strategies now in use throughout South Asian SAARC countries.

2. FAW distribution and prevalence in SAARC nations

For the South Asian sub-continent, FAW is an emerging invasive Lepidopteran pest species that is continuously ravaging maize and sugarcane in this region. Outside of its native habitat in tropical and subtropical regions of America where it is endemic, it has been first detected in Central and Western African nations, including Benin, Nigeria, Saotome and Principe, and Togo in 2016 [7].

As evidenced by Table 1 and Figure 1, the presence of the pest in SAARC nations was initially identified in a maize field located in the Chikkaballapur district of Karnataka state, India in May of 2018 [11]. Certainly, its discovery has raised significant concerns throughout the entire subcontinent. In less than five months of first appearance in maize, the invasive pest widely spread in five different provinces of India (Tamil Nadu, Andra Pradesh, Maharashtra, West Bengal, and Telangana) [2,12].

Importantly, the pest can easily expand to 400- or 500-kilometers distant places from its birthplace under favorable wind conditions as it has potential to fly more than 100 kilometers every night [7]. According to the survey by National Bureau of Agricultural Insect Resources (NBAIR) group in July 2018 under Indian Council of Agricultural Research (ICAR’s), FAW infected almost 70% of the maize fields of the Karnataka province, India and samples of its larvae were identical with those from Canada and Costa Rica (https://www.nbair.res.in/).

In Sri Lanka, FAW caterpillars were first detected in June of 2018 in the Ampara district of its Eastern Province [13]. The pest was also spotted in other districts sharing boundaries with Eastern Province of Sri Lanka in January 2019. It is believed it entered the island nation through the southern shore, possibly on agricultural products or by following wind currents from the nearest part of India.

Import of corn seed and corn-based food staff might be the key factor for the dispersal of FAW in Sri Lanka though the possibility of pest dispersal can’t be ignored through wind currents in Indian Ocean [13]. The close proximity of several SAARC countries, including Tamil Nadu (India) and Sri Lanka, west Bengal (India) and Bangladesh, west Bengal (India) and Nepal, and Panjab (India) and Panjab (Pakistan), facilitates the rapid spread of the invasive pest outside India.

Table 1 First report and distribution of FAW on maize and other host crops in SAARC nations.

Host crops	Country	Record year	References
Maize	Karnataka, India	2018	[11,12]
Ginger	Karnataka, India	2019	[22]
Maize, sugarcane, sorghum, sweetcorn	Tamil Nadu, India	2018	[21]
Sugarcane	Maharashtra, India	2018	[12]
Bajra, sorghum	Andhra Pradesh, India	2018	[23]
Rice	Karnataka, India	2018	[9]
Maize	Ratnapura, Sri Lanka	2018	[13]
Sugarcane	Sri Lanka	2019	[17]
Maize, fodder corn, sorghum, millet	Sindh, Pakistan	2020	[14]
Potato	Pakistan	2021	[24]
Maize	Bogura, Chuadanga, Bangladesh	2018	[16]
Cabbage	Rangpur, Thakurgaon, Bogura, Jashore, Bangladesh	2018	[17]
Maize	Nawalparasi, Nepal	2019	[18,19]
Maize	Bhutan	2019	[20]
Maize	Afghanistan	2019	[15]

In Pakistan, FAW first came to light in the southernmost province of Sindh in 2018 before spreading to other parts of the country [14]. A task group established by the Ministry of National Food Security and Research, Pakistan collaborated with international organizations like the FAO and the CIMMYT to monitor and halt its spread.

According to a recent report by FAO, the FAW was first found in Afghanistan in late 2018 and has since spread quickly across several provinces, including Balkh, Herat, Kabul, Kandahar, and Nangarhar in connection with maize production [15]. The report claims that border crossings, particularly those from near neighbors like Pakistan and Iran, are probably to blame for the fall armyworm's spread throughout Afghanistan.

In June 2018, following the discovery of FAW in India, Bangladesh began keeping an eye out for this polyphagous insect at her four separate maize and vegetable growing areas in Gazipur, Rangpur, Jashore, and Jamalpur with the help of the Entomology Division of Bangladesh Agricultural Research Institute (BARI). This monitoring continued until September 2018 in order to document the presence of FAW [16].

The mature foreign polyphagous FAW made its first appearance in Bangladesh at the end of 2018 in the maize fields of Regional Agricultural Research Station (RARS), Burirhat, and Rangpur, then in the fields owned by farmers in Bogura and Sherpur. In addition to maize, the pest has been recorded to also infest cabbage in various administrative districts of Bangladesh [17].

Researchers from the Nepal Agriculture Research Council (NARC) first documented FAW in Nawalpur, Nepal in May 2019 on maize. Within months, FAW was also observed in other districts of Nepal's mid-hills and mid-inner Terai (Kavre, Sindupalchowk, and Bhojpur) [18,19]. Since Nepal and Bangladesh share long borders with India, the dispersal of the pests is quite common across these regions.

In addition, the invasive FAW was first discovered in maize fields in the southwestern district of Samtse, Bhutan near the Indian frontier in July 2019 [17,20]. The Maldives have not yet received an official report of FAW infestation as of the time this study was written, but other Asian nations nearby, including China, Myanmar, Thailand, Vietnam, Malaysia, Japan, and Indonesia, have already acknowledged the presence of FAW in their countries [15].

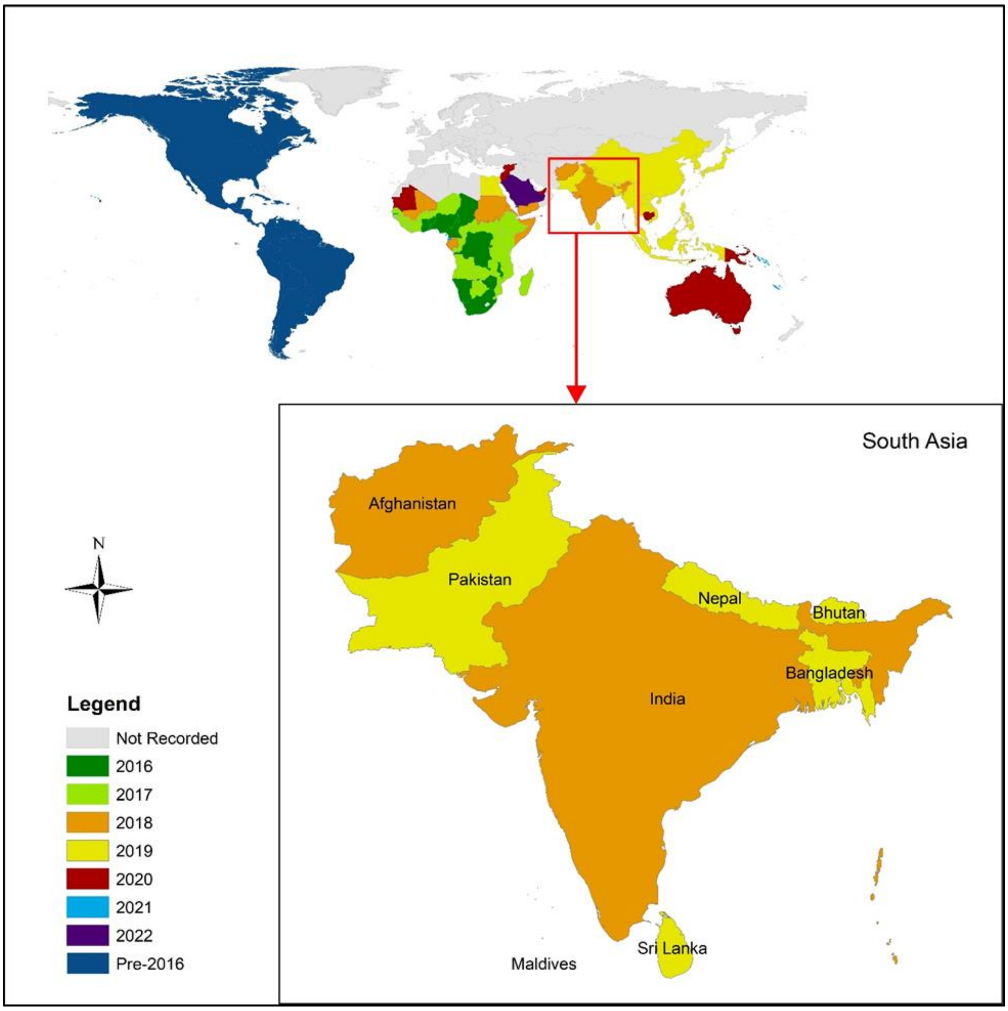

Figure 1 Distribution of fall armyworm (*Spodoptera frugiperda* J E Smith) in SAARC nations.

3. Host range and infestation pattern

The polyphagous FAW can infest a diverse array of plant species, including both cultivated and non-cropped plants alike totaling 353 plants in 76 families [5]. Although it primarily targets maize, it has the potential to attack other poaceous crops such as sorghum, sugarcane, rice, wheat, millet, bermudagrass, crabgrass, and other fodder grasses in the absence of maize [9,12].

It can harm up to 100% in its key host maize, and up to 30.86% in sugarcane and 10% in sorghum [12,21]. If monocropping is practiced over time, the infestation levels can increase to as much as 95% [25]. As demonstrated in Figure 2(A)-2(F), the FAW exhibits a feeding pattern encompassing all stages of maize growth, ranging from the emergence of seedlings to the development of ears.

Additionally, this pest is recognized for its highly voracious feeding behavior. FAW-damaged preliminary symptoms are similar to those of other stem borers with small holes and window pan feeding. The younger instars feed on leaves, while the later instars burrow into maize tassels and ears, wreaking havoc. The hallmark indicator of FAW larval feeding is the emergence of moist sawdust-like frass (fecal matter) around the feeding area of upper leaves.

An obvious sign that armyworm larvae are actively feeding during the vegetative stage of the maize plant is the appearance of skeletonized leaves. Excessive larval feeding on the foliage might cause harm to the development of the cob. Larvae can even kill the 'growing point' of immature maize, resulting in a 'dead heart' that hinders subsequent development and fruit production, resulting in yield loss [26].

Figure 2 Signature symptoms of fall armyworm infestation (A) windowpaning of leaves, (B) leaf holes and whorl damage, (C) tender leaf frasses, (D) mature leaf frasses, (E) larva on leaf, (F) 3rd instar larva on hand palm.

The host crop is directly damaged by the foliar feeding of FAW larvae and indirectly by the reduction of the photosynthetic surface area of the crop. Apart from cereals, numerous vegetable crops, such as tomato, okra, cabbage, and cauliflower, are susceptible to FAW infestation, which damages the leaves and lowers productivity [27].

However, foliar degradation in maize does not always result in yield loss since plants are capable of recovering foliar damage with sufficient nutritional and moisture management. Damage to sugarcane was similar to that of maize, but no dead heart indication was found in sugarcane. When maize was attacked between the first- and second-weeks following germination, yields were reduced by up to 22.6% [28].

The presence of up to 30 FAW larvae per plant resulted in significant leaf-feeding damage with no change in ear height, leading to a 13% reduction in maize yield [10]. Research has demonstrated that maize plants possess the capacity to mitigate the effects of damage sustained during the early stages of growth through the acceleration of new leaf and shoot development. The observed phenomenon could have facilitated the infested plants in sustaining a moderate level of productivity, notwithstanding the existence of fall armyworm.

4. Ecology and biology

Infestation intensity and yield loss have varied significantly across the Indian subcontinent, Africa, and America, depending on crop species, cropping season, and climatic conditions. Fall armyworm biology and infestation are significantly influenced by temperature and humidity in an agroecosystem. FAW larvae performed much better when kept at relative humidity levels of 50 to 90% and temperatures between 20 and 30°C [29,30].

In addition, it was shown that temperature and humidity had an impact on the FAW larvae's developmental period, with higher temperatures and humidity leading to shorter developmental times. High temperatures and humidity levels were shown to facilitate FAW infection in maize crops in another Indian study [31]. This study found that for feeding and growth, FAW larvae favored relative humidity values of 60-80% and temperatures of 24–28°C.

Temperature and humidity were found to have a significant influence on the oviposition and fecundity of FAW. Ecological conditions with a relative humidity of 60–80% and a temperature between 24-32°C are ideal for FAW moths to lay their eggs on maize plants. Because dry conditions can lead to the larvae becoming dehydrated and dying.

Fall armyworm larvae require a moist environment to maintain their physiological homeostasis via water balance [32]. Temperatures below 15°C and arid climates are intolerable to the FAW because the pest's metabolism slows down below 15°C, which limits its capacity to eat, develop, and reproduce. Drought or extremely low temperatures can restrict its distribution and population development [32]. It is quite apparent that high temperatures and relative humidity are ideal for FAW larval growth and survival and are more likely to result in severe infestations.

It is noteworthy that a range of variables other than temperature and humidity may also have an impact on the biological behavior of FAW. These include the quality of the host plant, naturally occurring predators, parasitoids, and pesticide use.

The polyphagous pest has a life cycle that includes four stages: egg, larva, pupa, and adult (Figure 3). The female moth typically deposits her eggs in batches of 100 to 200 on the underside of maize leaves, but in her preferred hot and humid climate, she can lay up to 1,500 eggs [29,33]. In two to three days after the eggs are laid, the larvae come out and start eating the leaves and burrowing into the corn. The larval development lasts between 14 and 21 days, and the larvae go through six instars during this time. The adult moth appears from the larval stage after about 10 to 14 days of pupation in the soil [34].

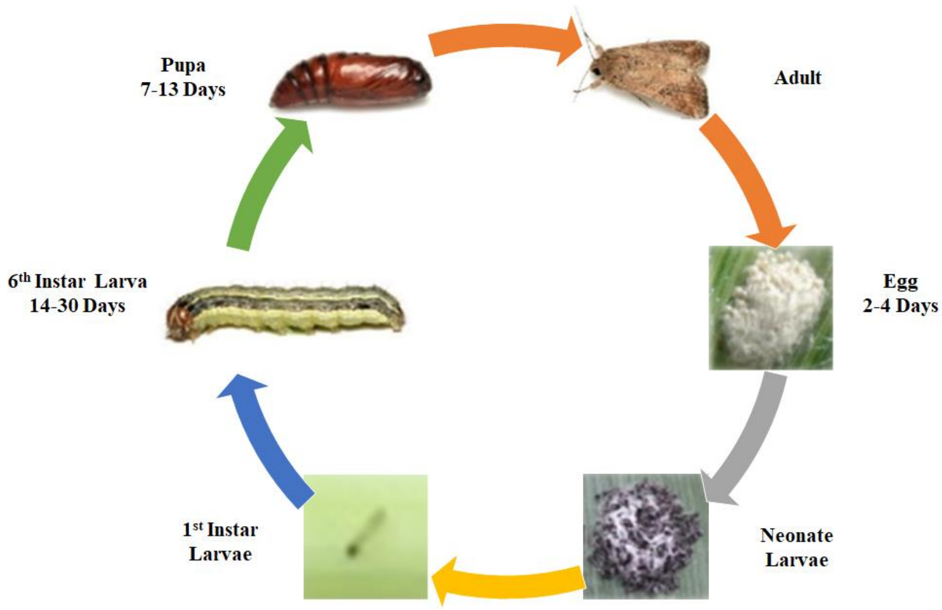

Figure 3 Life cycle of fall armyworm (*Spodoptera frugiperda* J. E. Smith).

For instance, fall armyworm development time was greatly shortened at temperatures of 25–30°C and relative humidity of 60–70%, leading to quicker reproduction and population growth [33]. High temperatures with low humidity can also boost fall armyworm reproduction rates. However, extreme temperatures or insufficient humidity exert adverse effects on their growth and reproduction.

Fall armyworm infestations follow a particular seasonal pattern, peaking during the time of hot and humid weather. In warm and subtropical areas like SAARC nations, these circumstances are frequently connected to the rainy season, which can create the best conditions for the pest's survival and reproduction. Numerous researchers have looked into the impact of the seasons on FAW infestations in South Asian SAARC countries. According to research done in India, FAW infestations were at their highest during the monsoon season, peaking around August and September [35]. Similarly, Nepal observed that FAW infestations peaked in August and were most prevalent during the monsoon season [18].

Similar to India, Bangladesh has two growing seasons for maize: Kharif (mid-March through mid-October comprising summer and rainy seasons) and Rabi (October through March comprising winter and spring seasons). Due to temperature variations, maize grown in the summer is more sensitive than that grown in the winter [36]. The winter temperature range (15–20°C) is unfavorable for Fall armyworm infestation in maize, resulting in minimal or no yield loss while the summer temperature range (25–30°C) encourages Fall armyworm to continuously infest the vegetative growth phase of maize, resulting in significant yield loss [36].

This research also discovered that temperature had an impact on FAW infestations, with higher temperatures and moisture causing enhanced infestations. Overall, a variety of elements, including temperature, moisture, the availability of host plants, and seasonal patterns, affect the fall armyworm's predilection for hot, humid climates. However, to guarantee timely and efficient control of FAW infestations, farmers and policymakers must take these factors into consideration when devising effective FAW management strategies.

5. Economics and yield damage

The discovery of FAW in South Asian SAARC countries poses a threat to numerous agricultural crops. The caterpillars of FAW devour hostplant leaves voraciously and have the ability to bore into the plant growing points.

FAW damage can significantly harm plant development, yield, and quality, resulting in substantial financial losses to the farmers.

For FAW infestations in maize, the economic injury level (EIL) and action threshold level (ATL) rely on a number of variables, including crop stage, plant population, and crop market value [10]. In South Asia, studies have calculated the EIL and ATL for the pest in maize under various conditions.

For instance, research done in India discovered that up to 12% yield reductions could occur at an infestation level of 2-3 FAW larvae per plant in the vegetative phase and 1-2 larvae per ear in the reproductive phase of maize [27,37]. Likewise, FAW infestation caused yield losses ranging from 17.7% to 33.3% across different maize varieties wherein the most substantial losses were noticed when the infestation level reached 4-5 larvae per plant [30]. An EIL of 3 larvae for each plant and an ATL of 2 larvae for each plant in maize were proposed by a different study from Bangladesh [36].

So, it was suggested that the application of insecticide was deemed not to be economically viable when implemented below the economic threshold (ET). In the Indian context, the economic threshold (ET) FAW is determined by the presence of 2-3 larvae per plant during the vegetative stage and 1-2 larvae per ear during the reproductive stage of maize where infestation levels of this magnitude have the potential to cause a 12% yield reduction in maize [31,37].

It is crucial to remember that EIL and ETL/ ATL for the pest can change depending on elements like weather, crop type, and regional management methods. As a result, it is recommended that farmers should seek the advice of local agricultural specialists to determine the suitable EIL and ATL for their particular farming circumstances.

With the reduction of maize output, FAW infestation incurs a massive economic loss in South Asia. For instance, research in India predicted that fall armyworm infestation could cause yield losses in maize of up to 20–30%, resulting in annual economic losses of about USD 2.5 billion [17].

Another study found that fall armyworm infestation in Nepal could result in maize yield losses of up to 100%, with an estimated economic effect of about USD 33.6 million [19]. With average yield losses of 20.5% for maize crops and losses varying from 10 to 30%, Sri Lanka experienced severe FAW infestation in the northern and eastern areas [13]. In Bhutan, the pest resulted in an annual economic loss of about USD 5.7 million due to estimated yield damage of 25.3% in corn [17].

Bangladesh is also experiencing considerable yield loss of maize and other cereal crops due to FAW infestation. According to a study in 2019, FAW infestation reduced maize crop yields by an average of 26.5%, with losses varying from 10 to 50% and late-planted crops experienced more damage [36]. Another investigation performed in Bangladesh in 2020 discovered that FAW infestation reduced maize crop yields by an average of 29.2%, ranging from 12 to 56%. Infestations were more severe in Bangladesh's southern region, which is known for its higher temperatures and humidity levels. Overall, these studies indicate that FAW infestations can result in yield declines of up to 10 to 56% in maize harvests in Bangladesh [32].

In Pakistan in 2020, researchers found that FAW infection decreased maize crop yields by 15% on average, with losses ranging from 5% to 30% [14]. According to the research, destruction was more severe in the southern region of Pakistan, which is known for its hotter climate and higher levels of humidity.

Cutworms, maize weevils, and fall armyworms are a few of the main pests that reduce maize yields in Afghanistan in which southern and eastern areas of Afghanistan have more severe FAW infestations, which reduce maize crop yields by an average of 30% with losses varying from 10% to 50% [15].

Timing and severity of the infestation, the stage of the crop, and the management techniques used can all affect the economic effect of FAW. To minimize the financial effects of FAW outbreak on maize, effective pest control methods, such as early diagnosis and judicious application of optimized integrated pest management (OIPM) techniques should be aided.

6. Management strategies

Judicious management lies on proper scouting and counting of the pest in the maize field to determine its EIL (economic injury level) and ETL (economic threshold level). If every whorl of maize meets 2 larvae or 5% of seedlings damaged by the pest or 15% of total crop stand at 30 DAP (days after planting) is infested by FAW, the crop stand should immediately be treated with appropriate control measures [10,37]. Since the pest is a voracious nocturnal feeder and enters into the growing points of maize, different management strategies should be applied in a compatible manner to effectively manage the pest below EIL.

6.1 Chemical Control

To control the unprecedented outbreak of FAW in South Asian region, chemical control is viewed as an emergency control measure [2]. A group of pesticides like abamectin benzoate, spinosad, and chlorantraniliprole is recommended by the Indian Institute of Maize Research against FAW to keep the infestation below ETL [31].

To stop the active larval feeding of FAW, delayed application of the prescribed group of pesticides is found to be inefficient. Since the larvae live inside the maize plant's funnel, the pesticide may not get into contact with them, making control less likely. It is advised to spray pesticides at dusk so it can reach the larvae coming out at night. The implementation of chemical control measures during the reproductive stage of a crop is not advisable as tassels would not have an impact on the yield.

Additionally, damage to corn ears cannot be prevented as larvae tend to conceal themselves within the ears. Handpicking combined with chemical control has been revealed to have a positive impact on controlling FAW infestation in South Asian regions [2]. Some of the frequent pesticides used in Africa for FAW management include methomyl, methyl parathion, endosulfan, and lindane; however, each of these chemicals is regarded as extremely dangerous pesticide and poses irreversible threats to human health and the environment [38].

In spite of the fact chemical methods for controlling FAW appear to be effective within a short period of time, the use of broad-spectrum and non-selective pesticides as a form of pest management for the pest is not recommended because it has a detrimental impact on FAW's biocontrol agents as well as a potential for the development of resistance in its populations.

6.2 Cultural control

In South Asia, cultural management techniques such as crop rotation, intercropping, planting date (early planting), and the planting of resistant maize types are effective in reducing the populations of FAW. Intercropping maize with legumes like cowpea, soybean, and pigeon pea decreased FAW infestations and yield losses of maize crops [39].

Likewise, a study done in Nepal found that growing maize and beans together increased maize yield and reduced FAW damage [17]. Similar conclusions were made both in Bangladesh and Pakistan regarding the effectiveness of early planting, intercropping, the use of trap crops, and resistant varieties in decreasing FAW damage to maize [17]. Similar to the rest of the world, trangenic maize varieties like Bt-Corn perform better in south asia than their native counterparts to withstand FAW infestations [40]. When combined with other management strategies like biocontrol and chemical pesticides, cultural management techniques can effectively control FAW infestations.

6.3 Biological control

The biocontrol technique for pest management primarily focuses on three ideas: conservation biological management (manipulating the agroenvironment and agronomic interventions favoring biocontrol agents' colonization), inoculative (introducing an exotic biocontrol species/ strains into an infested region via occasional field-release - successive generation control), and augmentative/ innundative (releasing biocontrol agents in large numbers against the target pest - single generation control) [41].
A detailed understanding of population dynamics and the behavioral ecology of natural enemies is a pivotal footstep in their introduction and colonization into a new agroecosystem [2]. There have been reports of 150 different parasite and parasitoid species on FAW, spread across 14 different families encompassing 9 different Hymenopteran families, 4 different Dipteran families, and 1 Neuropteran family. The two most abundant Hymenoptera families were the Ichneumonidae (with 36 species) and the Braconidae (with 28 species) while the Tachinidae family, with 55 different species, was the most diversified in the order Diptera, associated with lepidopteran pest management via parasitization [41,42]. As illustrated in Figure 4(A)-4(E), parasitic insects including Bracon, Telenomus, Chelonus, and Trichogramma have been proven very effective against the invasive FAW infestation in maize in many SAARC countries.

Parasitoid distribution varies among various agricultural environments. It serves as a biocontrol agent in nature by laying eggs on FAW egg masses, larvae, or adults, which then hatch and spread inside the host, finally killing it [43]. The parasitic insects *Telenomus remus* and *Habrobracon hebetor*, and the entomopathogen Spodoptera Nuclear Polyhedrosis Virus (sNPV), are commonly utilized to suppress FAW in SAARC nations [44].

However, the use of pesticides has an adverse effect on entomopathogens' activities, either directly through toxicity or indirectly through host death. At low cost, Parasites and parasitoids deliver comparatively long-term effectiveness, without inducing substantial resistance or imposing any harm to the environment [45]. To keep the FAW population below the economic threshold level on a sustainable manner, further widespread research is mandatory to recognize the native parasites and parasitoids.

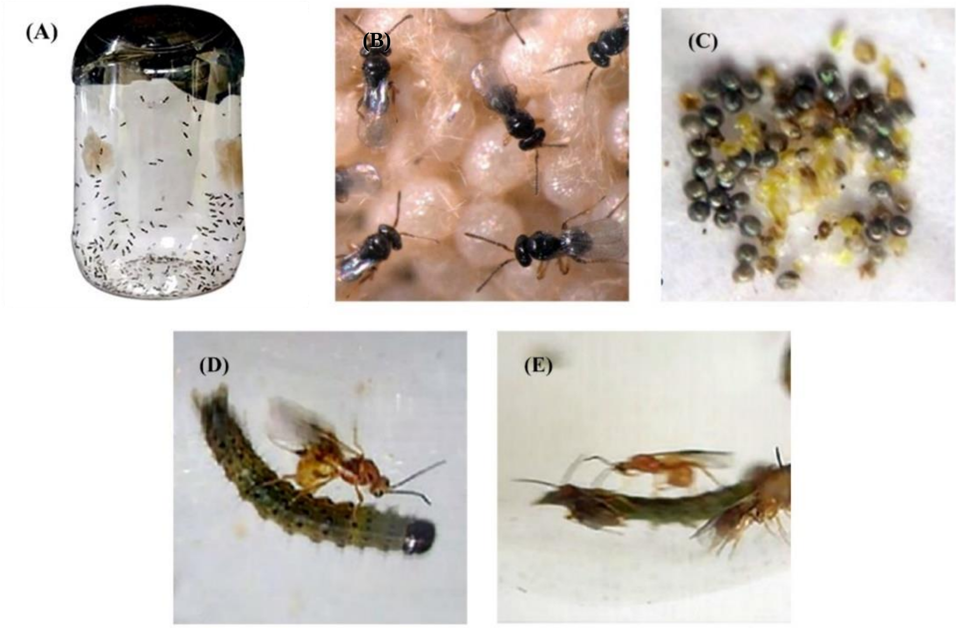

Figure 4 Parasitoid parasitism on fall armyworm larvae (A) *Chelonus* spp., (B) *Telenomus remus*, (C) *Trichogramma chilonis*, and (D-F) *Bracon hebetor* stinging, venom injection and larval death.

Another potential alternative to synthetic insecticides to manage FAW infestations is the widespread use of entomopathogenic fungi, bacteria and viruses (Figure 5(A)-5(F)). Research in India revealed that the entomopathogenic fungus *Metarhizium anisopliae*, *Bacillus thuringiensis* and *S. frugiperda* nucleopolyhedrovirus (sfNPV) were successful in reducing the number of FAW in maize fields [46].

Similarly, research in Bangladesh, Nepal and Pakistan also depicted that sfNPV is pretty useful in minimizing damage to the pest in maize [16]. sfNPV- infected larvae turn a bluish-black color, and move at a snail's pace, signaling the beginning of the end for FAW larvae and eventually dying off.

FAW larvae infected with the baculovirus, in particular, will typically be found hanging dead from the upper parts of maize plants [46]. More research is needed to develop effective and sustainable methods for mass-producing and applying these biocontrol agents in the field.

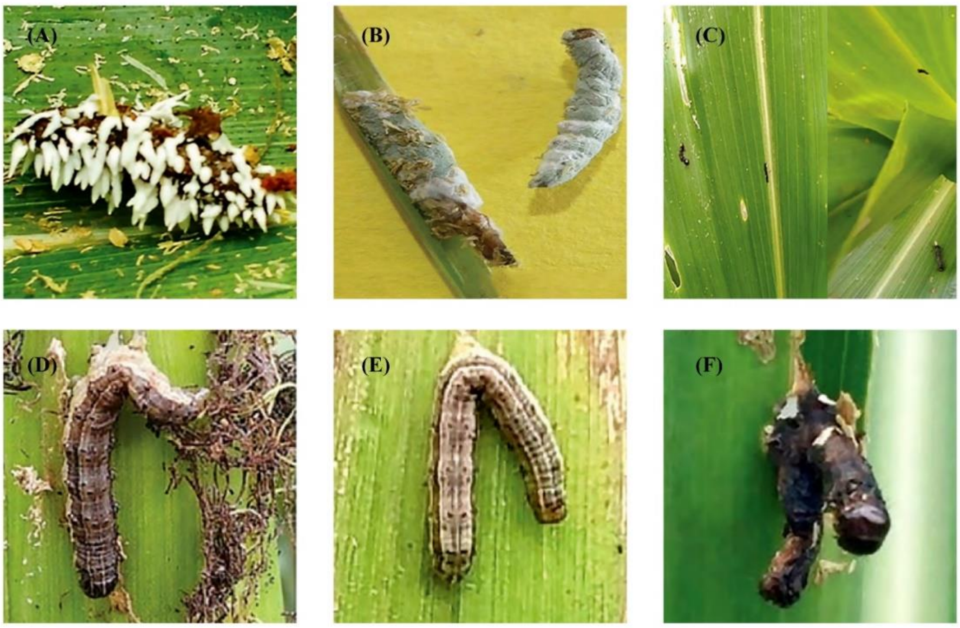

Figure 5 Entomopathogen pathogenesis on fall armyworm larvae (A) *Metarhizium rileyi* Mr, (B) *Beauveria feline* Bf, (C) *Bacillus thuringiensis* Bt, and (D-F) sfNPV (*S. frugiperda* nuclear polyhedrosis virus) infection.

6.4 Botanicals

To combat the fall armyworm in corn, botanicals have been proven useful. *Azadirachta indica* (neem), *Allium sativum* (garlic), and *Capsicum annuum* (chili) are three of the most promising plants widely used for controlling FAW [47]. The insecticidal and antifeedant activities of neem extracts have been shown, with azadirachtin, the active ingredient, inducing death and decreased feeding in FAW larvae.

Correspondingly, allicin and diallyl disulfide, the active compounds in garlic, have been demonstrated to be insecticidal, leading to death and decreased feeding in FAW larvae [48]. Capsaicin, the primary element in chili peppers, has been shown to have repellant and antifeedant characteristics, leading to decreased feeding and growth of FAW larvae [47]. In place of synthetic pesticides, some of which can be detrimental to people and ecosystems, these natural alternatives can be utilized.

Botanical extracts hold a specific active ingredient which is toxic for the targeted larvae of pest and non-toxic for the non-targeted organisms. Until the present, sixty-nine plant species have been found potential insecticidal and pesticidal activities against FAW [3,47]. An emulsion of 5% neem seed kernel has the potential to act as the repelling agent against FAW.

The larval death rate could increase by more than 95% by using botanical extracts of *Azadirachta indica*, *Schinnus molle*, and *Phytolacca dodecandra* [3]. In maize, the efficacy of *Nicotiana tabacum* and *Lippia javanica* was testified to cause up to 66% FAW larval mortality [47]. Garlic extract, neem, and detergent were used to make handmade botanical insecticides that performed and worked similarly to Solaris 6 SC, a synthetic botanical pesticide [41].

By identifying these locally accessible pesticidal plant species, there is a great likelihood of synthetic pesticides to be replaced with. Botanical extracts from plants that are pesticidal in action do not boost insect pest mortality rates the same way the synthetic pesticides do, but they can be a significant part of a sustainable agroecological pest management approach.

6.5 Integrated pest management (IPM)

It is more practicable to utilize an integrated pest management strategy to control FAW populations rather than relying solely on one method of management [45]. An integrated pest management program (IPM) is a comprehensive approach that includes a variety of control methods, including cultural, biological, and chemical controls, to minimize the damage caused by pests, while at the same time reducing synthetic pesticide use. IPM practices encompass not only curative approaches but also preventive techniques adopted before the infestation of pests.

Most of SAARC nations especially India, Pakistan, Nepal and Bangladesh highlighted the importance of IPM, which incorporates a variety of cultural practices such as crop rotation, intercropping, trap cropping, and biological control agents such as natural enemies and microbial agents for better management of FAW.

According to research from Ghana and Zambia, households that adopted at least one FAW management approach produced grain at a rate that was 43% greater than that of households that didn't [49]. Simple tactics like scouting, sticky traps, light traps, and pheromone traps are widely used to count EIL and ETL of the pest.

Adoption of feasible cultural approaches, maintaining soil health, judicious crop husbandry, and indorsing natural enemies along with compatible biological control methods can naturally suppress the FAW population in an agroecosystem.

Therefore, it is vital to encourage diversity on the farm by easy agronomic interventions like intercropping, mixed cropping, and alley cropping that would promote the richness of natural enemies and lead to the sustainable management of FAW.

7. Challenges

In South Asian nations, funding for agricultural research is scanty in comparison to the large population that has to be fed. The vast majority of farmers in rural areas are utterly unaware of government subsidy programmes, field experiments, crop clinics, and extension activities. Therefore, it is pretty challenging to instruct and educate the farmers themselves about pests and optimization of integrated pest management strategies to ensure sustainable solutions of the invasive pest FAW.

8. Future Directives

We should prioritize the development of early warning systems and surveillance tools to detect infestations of FAW in their early stages, allowing us to intervene promptly and manage the pest effectively. Furthermore, research into the effects of climate change on FAW populations and the efficacy of control measures in changing climatic conditions is necessary to be carried out.

It is important to promote the adoption of integrated pest management techniques, which include the use of cultural and biological pest control methods, to diminish reliance on chemical insecticides and lessen the potential for FAW pest population to build up resistance.

9. Conclusion

The swift expansion of FAW throughout different SAARC nations, first spotting them in India and subsequently infiltrating Bangladesh, Pakistan, Sri Lanka, Nepal, and Afghanistan, has put maize cultivation in peril. Considering the increased likelihood of pesticide resistance in FAW and the harmful consequences of synthetic agrochemicals on both the environment and consumers, it is of utmost importance to identify potential native natural enemies and entomopathogens, effective and compatible with region-based farming practices. Unlike the United States, the use of GM corn to prevent FAW damage is unanticipated and could be a very controversial choice for SAARC nations. Countries in this region, therefore, need to improve their collaborative research capacity to maximize the effectiveness of prevailing IPM techniques with a special focus on the use of context-specific cultural and biological methods that would ensure better control of the invasive pest and simultaneously minimize the negative environmental consequences. By implementing tailored IPM strategies, SAARC countries would mitigate the destruction of FAW on maize, ensuring sustainable agricultural practices and protecting food security, thereby fostering agricultural resilience and economic stability across the area.

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