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Bioscience Research

Print ISSN: 1811-9506 Online ISSN: 2218-3973

Journal by Innovative Scientific Information & Services Network

REVIEW ARTICLE BIOSCIENCE RESEARCH, 2024 21(1):01-13. **OPEN ACCESS**

Sustainable management and Bio-intensive control of invasive fall Armyworm, *Spodoptera frugiperda,* an emerging threat to maize

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The unexpected prevalence of the autumn armyworm of maize, *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera; Noctuidae), from the sprout through the cob production stage might result in a 100% yield loss. Maize farmers frequently use large amounts of insecticides to control this dangerous pest. This careless application of insecticides has caused an unacceptably high level of insect renaissance in maize, hurting both the production and utilization of maize. This summary provides an overview of practical pest control possibilities, such as plant host resistance, agronomical, cultural, biological, botanical, chemical and biotechnology strategies. It was found that the cultivation of tolerable genotypes, modification of planting windows, and application of specific cross-cultural and farming measures additionally provided favorable outcomes for long-term handling of fall armyworm, which might defend the crop, in addition to chemical-based and non-chemical insect control approaches. This analysis highlights cutting-edge and effective management strategies that are being promoted around the globe. The paper's recommendations would undoubtedly clear the way for the effective management of the FAW in maize and other vulnerable crops.

Keywords: agronomical practices; insecticides; effective management strategies; pest control; maize

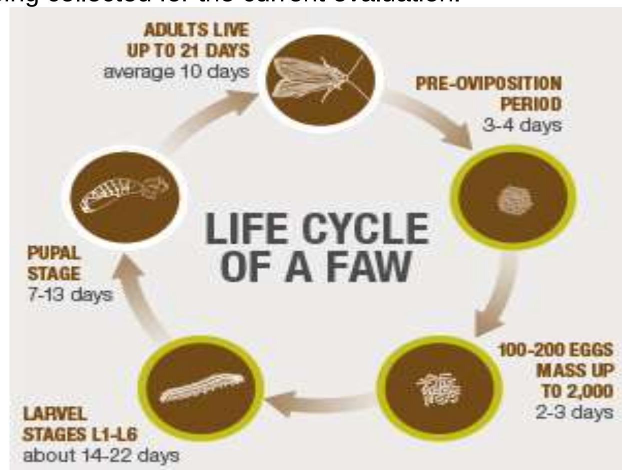
INTRODUCTION

A significant cereal crop grown around the world is maize (*Zea mays* L.), which has a flexible growth pattern and increased production. Growers are beginning to favour it more and more. 193.7 million hectares of land are used to cultivate maize, with a productivity of 5.75 tonnes per hectare. At the moment, 1147.7 million tonnes of maize kernels are grown annually (FAO, 2020). Over 100 nations cultivate maize for commercial purposes, with the United States, Brazil, China, and India largely assisting with global manufacturing. Although maize is an emerging crop in many regions of the globe, growers are drawn to cultivate it because of its superior efficiency in environments that are irrigated and nourished by rain as well as its simplicity. Due to its use in several industrial production processes, maize has currently replaced wheat and rice as the primary food crop (Andorf et al. 2019). In addition to being used specifically as animal and bird feed, maize is an essential source of raw materials for the production of corn oil, margarine, corn syrup, sweeteners, marmalade and instant non-dairy coffee creamer (Kaul et al. 2019). Among other things, maize is used to produce beverages, industrial chemicals, ethanol, gasoline, polymers, and high-quality paper (Naz et al. 2019; Gamage et al. 2022) Because of its numerous uses, corn's demand is constantly increasing. The development of elite cultivars with traits like herbicide resistance, drought tolerance, high protein content, and other characteristics was made possible by biotechnological advancements to satisfy the rising demand (Malenica et al. 2021).

Distribution, Spread, and Host Plants

The fall armyworm (FAW), *Spodoptera frugiperda*, is apersistent pest that is inhabitant to tropical and subtropical America and has rapidly spread throughout most of Sub-Saharan Africa (Brévault et al. 2018). It has also significantly spread across Western Africa. Over 44 nations on the African continent have now experienced its spread (Bueno et al. 2010; Nagoshi et al. 2018). The invasion started in India in 2018-2019 and spread to the majority of the Asia-Pacific nations within a year, including Korea, Japan, and Australia (Pogue, 2002; Prasanna et al. 2018). The tremendous migration force of the autumn armyworm is a significant hazard to crop plants' economic viability as well as a severe risk to newly formed environments in Africa and Asia (Deshmukh et al. 2020). Over 350 plant species are susceptible to damage by fall armyworm, including, but not limited to, maize, sorghum, rice, sugarcane, cabbage, beetroot, groundnut, soybean, onion, cotton, pasture grasses, millets, tomato, potato and cotton (Kenis et al. 2022). Maize is the most popular crop among all of them (Cock et al. 2017). A gregarious pest with migratory and localised spreading tendencies is the autumn armyworm. Like any other Spodoptera moth, it is capable of travelling more than 500 miles before oviposition (Navik et al. 2021). When the wind pattern is favourable, moths can fly up to 1600 kilometers (Cock et al. 2017). In many regions of the world, it only appears during specific seasons, but if an alternative host becomes available and the weather is agreeable, it can continue to reproduce year-round and expand to nearby regions. Armyworm in the autumn is widespread after a dry spell. Larvae are the stage of the bug that causes damage. The larvae have a variety of eating habits; for the most part, they wait until dusk to emerge from the soil or the mouths of plants to feed. The day-feeding autumn armyworm is active all day long, though. According to Day et al. (2017), if autumn armyworm is not controlled, maize output losses could range from 8.3 to 20.6 million tonnes year (21-53 percent of total production). Similar to this, other investigations also showed significant yield loss, observing 11.6% yield loss, Kumela et al. (2019) 32-47% yield loss, and Day et al. (2017) 22 and 67% yield loss (Hafeez et al. 2021).

Insects often gather and migrate to regions that are otherwise out of their reach, but maize crops in irrigated environments offer hospitable conditions that support their survival (Navik et al. 2021). Additionally, the widespread cultivation of other preferred hosts (such as sorghum, rice, sugarcane, cabbage, beetroot, groundnut, soybean, onion, cotton, pasture grasses, millets, tomato, potato and cotton) in most maize-growing nations in Asia and Africa has made the overall pest situation worse as a result of pest population shifts from one host to another. As a result, it has become commonplace to encounter autumn armyworm in maize over time. Therefore, it is crucial to create management strategies for this invasive insect pest of maize to guarantee the safety of the world's food supply and nutrition. Numerous management strategies have been promoted globally (Westbrook et al. 2019) as a result of the prevalence of autumn armyworm and the large potential losses it may cause. The majority of the sustainable management choices available globally are being collected for the current evaluation.



Figue1. Life cycle of FAW

Life cycle

To create effective control plans, a thorough comprehension of the biological cycle of insect pests is required. The biology of the FAW varies depending on its habitat (Figure 1). The insect's life cycle lasts about 30 days in summertime conditions in the USA (daily temperature of 28 °C), but it can take up to 60-90 days in the spring and winter (Pogue, 2002). 13.01 °C and 30 °C, respectively, are the minimum and maximum thresholds for the formation of FAW (Day et al. 2017). The amount of autumn armyworm generations in a region varies according to the countenance of the adults who are scattering and the weather (Pogue, 2002; Baudron et al. 2019)]. Each adult female could lay between 1500 and 2000 eggs, which she did in groups on either side of the leaf. Eggs are dome-shaped, 0.3 to 0.4 mm in diameter, and incubate for 2–3 days. Six instars were seen during the summer; the young larvae had greenish bodies and black heads. It's interesting to note that Wu et al. (2020) observed that invading bet-hedging strategy populations of *S. frugiperda* allow for rapid breeding and longer reproductive lifespans and that this behavior supports the success of the species' invasion. The head of the adult larva is reddish-brown in color and has a brownish body. A completely grown larva has been identified by a white inverted "Y"-shaped suture. Pupation occurs in a dirt cocoon that is typically oval in shape and is 20 to 30 mm in diameter. The cocoon is located at a depth of 2 to 8 cm. The pupa has a reddish-brown tint, is 14–18 mm long, and is 4.5 mm wide. Its pupal phase lasts 8–9 days. The hind wings of the adult are silvery-white with a little dark mark along the margins and are colored in shades of grey and brown. The adult is nocturnal and only emerges at night during hot, humid conditions. Adults typically live between seven and ten days (Cock et al. 2017).

Nature and Destruction Signs

The larvae of FAW are the most bothersome stage. The opposing epidermal layer is unaffected while the young larvae eat first on the dorsal portion of the leaf blade. Young leaves are pierced by second or third-instar insect larvae. The larvae begin to graze from the leaf's edge inward as they get older. This first affects the leaf in its whorl; when the leaf has fully expanded, the damaged plants display recognizable shot hole symptoms (Du Plessis *et al.* 2020). Although immature larvae become more aggressive at the beginning of their development, later instars often exhibit a reduction in larval numbers and, as a result of cannibalistic activity, only one to two larvae are typically seen per plant (Shylesha et al. 2018). Later stages of larval development result in significant defoliation (Pogue, 2002). In unregulated or unmanaged environments, larvae quickly consume all the green leaves, leaving just leaf ribs and stalks that finally seem ripped. In terms of crop sensitivity, the early whorl stage is the least sensitive, followed by the mid-whorl stage and the late whorl stage. Production can be reduced by 5 to 20% at mean densities of 0.2 to 0.8 larvae per plant during the late whorl stage. Larvae also climb up to the ear and eat the kernels when there is a very high infection rate, completely reducing the yield.

In many nations, the rising desire for maize kernels on local, national, and worldwide markets provided market confidence by suggesting premium pricing. Maize has supplanted some crops and cropping techniques in the majority of African and Asian nations due to its photo- and thermal insensitivity, favorable market price, and simplicity of production. Recently, due to ongoing monoculture and monocropping, various pests have begun to harm maize. More than 25 distinct insect pests are now affecting maize at various phases of crop growth. One of them is *Spodoptera frugiperda*, a damaging pest with a broad host range that severely reduces production over a sizable infection region (Pogue, 2002; Shylesha et al. 2018; Wu et al. 2021; Wan et al. 2021; Kumar et al. 2015).

Management techniques

Agronomy Management

Seedling windows

The atmosphere in which cultivation grow is altered by the planting dates (Rahmathulla et al. 2012). The agroecosystem includes pests as a necessary component. Temperature, relative humidity, rainfall, and other weather factors have a big impact on insect infestation and population growth. Environmental factors have an impact on the survival, growth, and ability to reproduce of insect pests (Mitchell, 1978). Fall armyworm typically occurs towards the end of the growth season. Therefore, delay seedlings of Kharif crops should be avoided to prevent its infestation. Additionally, the earliest and smallest sowing windows should be used to plant kharif maize to prevent the host range from remaining continuously available (Teare et al. 1990). Additionally, harvesting earlier assists maize ears in avoiding the larger levels of armyworms that develop later in the season. Further supporting the benefits of early sowing is the finding from Teare *et al*. (1990) study that fall armyworm of maize was not a serious issue in early-planted maize. Autumn armyworm is predicted to have an impact on Nepal's use of late-maturing hybrids and late-planted maize crops, according to Kandel and Poudel, (2020). According to a recent study by Food and Agriculture Organization (2018) (FAO, 2018), late-planted maize plots had much greater production losses from fall armyworms than nearby early-planted plots. Therefore, in endemic patches of autumn armyworm in US maize belts, early planting and adoption of short-duration genotypes are precise practices (Tippannavar et al. 2019). If maize is planted ahead of schedule, the pest won't arrive at that time, protecting or lessening damage to the crop, claim Bhusal and Chapagain, (2020).

Preparing the Land and Tillage

The dynamics of the agro-pest ecosystem are significantly influenced by tillage and soil management (Alyokhin *et al.* 2020). It is a proven truth that frequent and intense land disturbances harm soil by promoting erosion, reducing organic matter, and having a detrimental effect on all soil organisms (Rowen et al. 2020). Despite having several negative effects on the sustainability of agroecosystems, tillage is the utmost widely employed agro-technique in growing crops globally for both managing pests and preparing fields for sowing (Lal et al. 2007). This is particularly true when it comes to controlling the autumn armyworm in maize. The fully developed larvae make a reddish-brown oval cocoon that is about 2-3 cm long and drop to the ground to pupate. They can burrow 2 to 8 cm in soft soil, but in hard soil, they can spin a webbed cocoon under leaf debris. These pest propagules help the pests finish their life cycle and multiply further. According to Kumar and Mihm, (2002), compared to traditional tillage methods, undisturbed soil conditions resulted in a 30–60% lower autumn armyworm infection rate, which may be attributable to the presence of significant predators. According to Clark, (1993) reduced-tillage maize fields had more carabid beetles, rove beetles, spiders and ants than standard-tillage fields, which were all important fall armyworm predators. They also found that the farms with the largest predator populations had the highest mulch coverage and the lowest tillage intensity. Baudron *et al*. (2019) and Roberts and All, (1993) both observed similar reductions in autumn armyworm infestation with no tillage. In a maize-wheat cycle conservation agriculture system in central Mexico, Rivers *et al*. (2016) discovered noticeably higher spider activity in no-till maize and with residue retention in wheat, as well as enhanced autumn armyworm predation after planting in maize. For instance, the study by Kumar and Mihm, (2002) revealed that when compared to conventional tillage methods, zero-tillage consistently reduced fall armyworm damage and increased yields by about 10%. Minimum tillage practices lower fall armyworm infestation rates in Africa's maize belts, according to early research from Zimbabwe.

According to other research findings, tillage has the potential to be an effective technique for controlling autumn armyworms. It involves little alteration of the soil and the preservation of residue, can be easily incorporated into existing control efforts, and can help conservation farming fulfill its role in sustainable intensification and climate change adaptation (Thierfelder *et al.* 2015; 2016). Furthermore, Harrison *et al*. (2019) examined how agroecological methods of managing pests, like land tilling, bund growing, and soil fertility management; provide effective and reasonably priced pest control techniques that are simple to integrate into continuous insect control programs.

Nutrient Management

Healthy plants and crops are produced when crop nutrition is balanced, and these plants and crops are more likely to withstand biotic and abiotic challenges [27. Thought-enhanced insect damage is made possible by unbalanced crop nutrition (Altieri *et al.* 2003). According to Morales *et al*. (2001), the use of inorganic fertilizers promoted the growth of herbivorous pests in maize fields, such as autumn armyworms. Crops fertilized with inorganic fertilizers showed a higher prevalence of aphids than crops fertilized with organic fertilizers, according to a study by Morales *et al*. (2001). Particularly with nitrogen, inorganic sources of plant nutrients, such as chemical fertilizer additions, guarantee a rapid supply of plant nutrients after their application. Numerous studies (Altieri and Nicholls, 2003); Morales *et al.* 2001) have shown that this increase in nitrogen concentration in plant tissues makes them more appealing to insect herbivores. Additionally, Baudron *et al*. (2019) found that plots with nitrogen spray had a greater frequency of autumn armyworm in the maize belts of Eastern Zimbabwe. According to research done on Bermuda grass (Singh et al. 2020), potassium inhibits fall armyworm growth and development whereas nitrogen encourages it. The C4 family includes the nutrient-dense crop maize. It always tempts the producer to use more nitrogenous fertilizer, which causes an imbalance in the nutrition of the crop (Kumar *et al.* 2015). This may be the main element promoting the infrequent occurrence of autumn armyworms in maize over time. Therefore, attention should be paid to ensure balanced crop nutrition while implementing integrated management of biotic stress in general and autumn armyworm in particular. In contrast to degraded soils with low organic carbon content, Altieri and Nicholls, (2003) observed a decreased abundance of insect herbivores and active soil biology in high organic matter soils.

Cropping System mechanism

In contemporary intensive agriculture, growing crops in combination or succession is an ambiguous practice. Distinct plant varieties being grown on similar plots of land contribute to environmental variety and wealth. Bi-cropping is the practice of simultaneously cultivating two crops with different augmentation tendencies on a similar plot of ground (Cannon et al. 2020). In the ancient agricultural framework, bi-cropping has many benefits over solitary planting, including assurance against pests and unusual weather (Sida et al. 2018). Bi-cropping can reduce pest damage (Midega et al. 2011) by improving soil quality, promoting vigorous plant growth, limiting insect migration, preventing insect egg-laying through visual or chemical disturbance, and providing shelter for natural enemies. According to studies by Altieri et al. (1978), intercropping maize with beans reduced autumn armyworm infestation by 23% when compared to maize cultivation on its own. Beans planted up to a month before maize considerably decreased FAW infestation, according to Altieri, (1980). Similarly, intercropping maize and beans in Nicaragua reduced FAW infestation by 20–30% (Khan et al. 2010). The decline in pest load on maize under intercropped conditions may be brought on by restricted larval dispersal given that the different component crops contained the larvae in the inflated instar (Harrison *et al.* 2019). Moreover, the wide range of species of crops grown in the same region contributes to the existence of natural enemies in agro-ecosystems, as shown by Van Huis, (1981) who reported higher densities of natural enemies, such as earwigs and spiders, feeding on early larval instars under maize polyculture systems. As a method of weed control, maize growers in East Africa typically intercrop maize with plants that release volatile pest repellents, including Desmodium spp. (Family: Fabaceae), which has also been reported to be effective in the management of autumn armyworms. The autumn armyworm incidence decreased in this system by as much as 86%. It consequently caused maize grain yields in East Africa's drought-prone regions to grow by 2.7 times (Midega et al. 2011) Similar to how maize draws autumn armyworm more than bund-planted *Pennisetum purpureum Schumach* of the Poaceae family. This is also applied when applying targeted pesticides. Intercropping leguminous crops with maize significantly reduced autumn armyworm compared to mono-cropped maize, especially during the early phases of the maize's growth up to tasselling. Therefore, plant species that produce semiochemicals may be used in cropping systems to develop integrated management methods against fall armyworms. Legumes interculturalists help reduce FAW damage in maize, according to various research investigations from throughout the world (Midega et al. 2011; Khan et al. 2007; Tanyi et al. 2020).

Trap Crops

Trap crops are intended to draw pests away from main crops, thereby guarding against attack (Patil et al. 2017). The trap crop may belong to the similar specie as the primary crop or to a different one. There are two techniques to plant trap crops: row intercropping and perimeter trap cropping. Perimeter trap farming is the practice of planting trap crops all around the main cash crop. It protects against pest attacks coming from all directions. It works well against pests that are present near the farm's boundaries. The main crop is grown in intercropped rows while the trap crop is sown in alternating rows. There are various benefits of trap crops for pest management. Major crops rarely need insecticide treatments because trap crops that effectively attract pest populations limit infest to cash crops (Patil et al. 2017). In the majority of the places of the world where maize is grown, the autumn armyworm is a relatively new pest. There is a dearth of information on trap cropping as a management strategy for autumn armyworms. On the other hand, Mooventhan et al. (2019) advise planting 3–4 rows of Napier grass around maize fields and spraying the trap crop as soon as it exhibits signs of fall armyworm damage with 5% neem seed kernel extract or azadirachtin 1500 ppm. More oviposited eggs were also seen on the Brachiaria hybrid cv. Mulato II (Family: Poaceae), *Panicum maximum* cv. Mombasa (Family: Poaceae), and *Panicum maximum* cv. Tanzania (Family: Poaceae) than on maize, according to Guera et al. (2020). The "Push-Pull" cropping technique, which combines intercropping pest-repellent ("push") plant species, such as Desmodium spp., with a pest-attractive trap ("pull") plant species on the borders, such as napier grass (*Pennisetum purpureum Schumach*.) or Brachiaria spp., could also use trap crops. The autumn armyworm infestation and crop loss were entirely reduced by 86%, and productivity increased by 2.7 times for farmers in East Africa who utilised the Push-Pull method exclusively (Midega et al. 2011).

Pheromones Traps

Pheromones are odors that males and females emit that cause one or more behavioral responses in the other sex, luring them to mate. Because these compounds lead insects to become confused and become caught, the application of pheromones primarily lowers the rate of insect reproduction in the target area (Jiang *et al.* 2020). The primary component (Z)-9-tetradecyl acetate (Z9-14:Ac) and the minor component (Z)-7-dodecyl acetate (Z7-12:Ac) make up S. frugiperda's female pheromone, which attracts male moths (Cruz et al. 2012). The trace element (E)-7-dodecyl acetate (E7-12:Ac), which varies geographically, has only been identified in Brazilian females thus far. In terms of pest control, it's critical to keep in mind that the autumn armyworm is made up of two strains (corn and rice) with various pheromones (Kenis *et al.* 2022). Pheromones have long been employed to track the male population, and in the case of the autumn armyworm, the female's sex pheromone is commercially available in several nations (Cruz et al. 2012). Pheromone trap monitoring is helpful since pest infestation changes over time and from farm to farm. An early warning system that enables field sampling and treatment is provided by knowing when and where the adult pest is active and abundant. Knowing if pests were present or absent allowed the planter to avoid wasting pesticides or taking time-consuming samples. When moth flight was first discovered, he was also given the warning to protect crops (Cruz et al. 2012). Male moth larvae destroy plants, although adult moths are caught in traps. This means that we cannot simply estimate the number of moths in the traps while ignoring other variables such as crop stage, temperature, and possibly natural management. Temperature and wind speed have a positive correlation with trap catches, whereas relative humidity has an adverse correlation. The best way to determine how many treatments of insecticide are required to eradicate the pest from maize is to use traps that emit pheromones to track mature fall armyworms (Batista-Pereira et al. 2006).

Biotechnological Method

Resistance in Plants

A cheap and possibly successful strategy for controlling insect pests is host plant resistance. It generally contributes to sustainable production because it is affordable, reliable, clean, and adaptable to local conditions. Several plant morphological features that contribute to antixenosis have been used to create genotypes that are resistant to fall armyworm. The larval stage, metabolised food, and insect stool mass are among them, and Sanches et al.'s seminal study (Sanches et al. 2019) identified these as key elements that affect fall armyworm resistance. They discovered three maize genotypes that show promise for providing resistance to the autumn armyworm: BOZM 260, PA 091, and PARA 172. Similar to this, Chen et al. (2009) claimed that maize accession Mp708 and FAW7050 were resistant to fall armyworm because of improved defence protein, higher levels of amino acids and glucose, and constitutive accumulation of jasmonic acid. According to a study by Smith et al. (2012), the display of autumn armyworm resistance is caused by (E)--caryophyllene, a terpenoid produced constitutively in a maize line called Mp708. Furthermore, Ni et al. (2011) research revealed maize germplasm Mp708 and FAW7061 to be two of the most resistant cultivars to fall armyworm infection.

Genetic Engineering

Normal agricultural practices frequently involve the use of synthetic chemical pesticides. Pests are destroyed when they come into contact with the deadly agent used for chemical control. Only after the plant exhibits the expected symptoms are the chemicals sprayed. Because caterpillars are typically located in maize whorls, where they are typically protected from insecticide treatments, this method is typically ineffective for managing autumn armyworms (Hruska, 2019). Conversely, the FAW exhibits worldwide resistance to more than thirty pesticide-active components across all main classes. Thus, a practical approach to managing pests is to use genetically engineered maize that is resistant to fall armyworms (Li et al. 2020). To control the autumn armyworm, genetically altered crops are effective in China (Li et al. 2021). In many parts of the world, with adoption rates of over 80% (Romeis et al. 2019), genetically modified crop types that express insecticidal crystalline (Cry) or vegetative insecticidal proteins (Vip) produced from *Bacillus thuringiensis* (Bt) that are selectively poisonous to distinct insect species are planted to control caterpillar pests. Some pests that were already established have experienced area-wide population declines as a result of widespread adoption and the high control efficacy offered by genetic engineering (Li et al. 2020). Additionally, Bt maize hybrids are frequently employed in America to control the autumn armyworm (Hruska, 2019; Li et al. 2020). Due to the restricted range of activity of the deployed Cry and Vip proteins, growing Bt crops has assisted in reducing pollution by reducing the need for chemical insecticides and assisting natural pest management (Romeis et al. 2019). According to Li et al. (2021), genetically modified maize should not be seen as a substitute for conventional autumn armyworm management strategies but rather as an addition to them (Li et al. 2021; Tabashnik et al. 2017)

Gene Editing Approach (CRISPR-Cas System)

Although transgenic (Bt) crops have significantly improved crop protection, insect resistance has plagued the technology, prompting the development of more recent biotechnological methods for controlling insect pests, such as gene editing (RNA interference (RNAi); gene drives; and, most recently, the CRISPR-Cas9 system) (Li et al. 2021); Ullah et al. 2022). Researchers can employ gene editing technologies to validate gene activity, which will help them better understand the resistance mechanism and develop novel pest control methods. CRISPR-Cas application in plants was accomplished effectively in the lab in 2013 (Books, 2019).

Based on his findings, Wu, (2020) concluded that the autumn armyworm's abdominal-A homeotic gene was deleted by CRISPR/Cas9 technology, suggesting that the method is very effective for editing the autumn armyworm genome (Zhu et al. 2020)

Chemical Management

Poisonous Baits

Pesticides that are fatal to the pests they are intended to control can be combined with benign food additives to create poisonous baits. The application of chemical bait in whorls at the vegetative stage and dissemination in the mature crop has both shown promising results in suppressing infestations of autumn armyworms (Bhusal and Chapagain, 2020). In India, Patil et al. (2017) described the procedure for making poison bait, which involved combining 5.0 kg of jaggery with 4-5 L of water. 625.0 mL of monostrophes 36 SL were added to this solution. This mixture was then combined with 50 kg of rice or wheat bran, sealed in plastic or gunny bags, and left to ferment for 48 hours Application of this fermented bait, preferably in the evening, by broadcasting or insertion into maize whorls, greatly decreased the prevalence of autumn armyworm in maize.

Insecticides

It is a controversial practice to use different insecticides to manage crop pests (Baranek et al. 2021; Liang et al. 2021; Gul et al. 2021). Insecticides are categorized into systemic and contact insecticides based on their method of action. The FAW larva feeds by staying inside the maize whorl and avoiding contact with applied insecticides. As a result, various systemic insecticides were investigated for use against the maize fall armyworm. Emamectin benzoate 5 SG application demonstrated the highest acute toxicity among them, followed by chlorantraniliprole 18.5 SC and spinetoram 11.7 SC. However, the leaf-dip bioassay revealed similar acute toxicity for flubendiamide 480 SC, indoxacarb 14.5 SC, lambda-cyhalothrin5 EC, and novaluron10 EC. However, when used in the field for evaluation, it was discovered that lambda-cyhalothrin 5 EC, novaluron 10 EC, spinetoram 11.7 SC, flubendiamide 480 SC, and chlorantraniliprole 18.5 SC were all superior (Pogue, 2002). In another study, profenophos + cypermethrin, spinosad, profenophos + lambda cyhalothrin, and indoxacarb were found to be the most effective at killing sixth-instar larvae in whorls. In another study conducted in Ethiopia by Sisay et al. (2018), synthetic pesticides such as Lambda-cyhalothrin 5 EC, chlorantraniliprole 20 SC, Spinetoram 120 SC, dimethoate 40 percent, Tracer 480 SC, and Ampligo 150 SC drastically reduced fall armyworm larval mortality, reduced leaf damage, and raised biomass in maize. The application of systemic insecticides seems to be the most promising part of integrated pest control approaches for FAW, according to these recent studies. This latest research suggests that the most promising aspect of integrated pest management strategies for the autumn armyworm is the use of systemic insecticides. Since there are currently no recommended pesticides in use in nations like India, where the pest has just invaded, the suggestion has been issued by the Central Insecticide Board and Registration Committee. The committee advises using spinetoram 11.7 SC, thiamethoxam 12.6% + lambda-cyhalothrin 9.5% ZC, and chlorantraniliprole 18.5 SC for the control of autumn armyworms. However, the potential widespread application of these chemical insecticides could result in hormesis effects, a pest rebound, and the emergence of insect pest resistance (Ullah et al. 2019; Ullah et al. 2020;

Wang et al. 2021; Cutler et al. 2020; (Gowda et al. 2021). Additionally, these pesticides may negatively affect human health and non-target creatures in many ways (Desneux et al. 2007; Babin et al. 2022; Akhtar et al. 2021).

Biological Management

Biological Techniques

FAW treatment via biological methods has been suggested as a potential substitute for chemical methods (Hou et al. 2022; Gowda et al. 2021). Numerous natural enemies of this bug have been found to exist in diverse locations. 150 species of FAW-related parasitoids and parasites from the Americas and the Caribbean basin were cataloged by Molina-Ochoa et al. (2003). Shylesha et al. (2018) found parasitoids and predators targeting this pest at several stages of maize in India, such as eggs, larvae, and larval pupals. Numerous ground beetles (Coleoptera: Carabidae), the striped earwig Labidura riparia (Pallas), the spined soldier bug Podisusmaculiventris (Say), the insidious flower bug Oriusinsidiosus (Hemiptera: Anthocoridae), and the earwig Labidura riparia (Say) were discovered to be effective predators against the fall army (Pair and Gross, 2012). Although predators have a substantial impact on autumn armyworm survival and growth, parasitoids outnumber predators in terms of their ability to kill off autumn armyworm populations. The larvae of S. frugiperda were found to include solitary parasitoids of the Hymenoptera genera Chelonus and Campoletis (Tendeng et al. 2019), and Trichogramma parasitoids may be highly effective biocontrol agents for the creation of inundative biological control programs (Huang et al. 2020; Zang et al. 2021; Zhang et al. 2021). In three East African nations in 2017 (Sisay et al. 2018), five parasitoid species from the autumn armyworm were identified. An essential part in controlling S. frugiperda is played by the larval endoparasite Campoletis species (Molina-Ochoa et al. 2003). The parasitoid C. flavicincta's larvae naturally inhabit the autumn armyworm as a host. The S. frugiperda larva begins to construct its cocoon, which permits it to continue developing until it emerges as an adult. The identification of potential natural enemies and disease-causing microorganisms must be prioritized at this time to control S. frugiperda biologically. Chemical insecticides can be replaced by eco-friendly, long-lasting, and appropriate biocontrol and biopesticide methods (Santoiemma et al. 2020). These methods provide a solid foundation and are the mainstay of any integrated pest management (IPM) programmed. By introducing naturally occurring disease-causing illnesses as natural regulating agents, Fall armyworm can efficiently manage insect populations (Akutse et al. 2020). To reduce the quantity of autumn armyworms, several microbial diseases have been researched. Autumn armyworm is attacked by more than 53 parasite species, including 43 genera and 10 families (Assefa, 2018). The Cry1F protein is believed to be more toxic to autumn armyworms than any other Cry protein, although commercial Bt isolates have not been developed to combat autumn armyworms (Franz et al. 2022). There have also been numerous reports of predators that prey on autumn armyworm eggs and larvae.

One of the key biocontrol agents of FAW is insect pathogenic viruses. Ascoviruses, Baculoviruses, Densoviruses, Rhabdoviruses, and Partiti-like viruses are just a few of the viruses that are known to infect FAW larvae (Hussain et al. 2021). Baculoviruses are the most promising of them. Recent technological developments have increased the marketability of virus products for the control of many insect pests worldwide. SfMNPV, a baculovirus that infects S. frugiperda, has been approved for commercial use and registered in many nations for the control of FAW (Valicente, 2019; Lei et al. 2020; Souza et al. 2020)

Bird Perches

It has been discovered that a wide variety of insectivorous birds eat crop-problem insects (Nyffeler et al. 2018). It has been documented that these insectivorous birds may eradicate up to 84% of the larval population (Patil and Gaikwad, 2021) Many birds that live in farmed areas actively hunt down and eat caterpillars in crop plants, according to Jones et al. (2005) Among predatory birds, the black drongo, house sparrows, blue jays, cattle egret, rosy pastor, and mynah are frequent insectivorous birds that consume a lot of lepidopteran insects. Large size larvae exhibit a high attraction to insectivorous birds (Jones et al. 2005). FAW larvae that have avoided parasitism grow more quickly than those that have been attacked by Euplectrus wasps in the case of environmentally friendly pest control (Jones et al. 2005). In addition to offering perches and roosts for birds and bats, boundary trees (such as fodder, fuelwood, and shelter trees) help increase the structural variability of the farm environment by offering shade and shelter (Harrison et al. 2019). These bird species can remove fall armyworm larvae from the whorls and husks of maize plants. Based on these findings, it was established that insectivorous birds are another viable weapon for the environmentally benign and long-term control of maize fall armyworms. Because maize is an agricultural plant without branches, birds are less likely to perch there for extended periods. For this reason, it's critical to construct suitable live bird perch in an environment of maize. The maize field must be planted with a variety of rapidly growing plants that provide a stable platform for insectivorous birds from the growing phase to crop maturation. This will stimulate bird visits.

Use of Botanicals

Many plants in the natural world have insecticidal qualities. Botanical pesticides are products created using those plant materials. These natural insecticides are produced or derived from plants or minerals and are found in nature. A study of the utilization of botanicals in pest management was prompted by a rise in interest in the sustainable control of pests in the majority of edible crops. The use of botanicals for pest control has little impact on the environment and is safe for both humans and animals. The autumn armyworm has a propensity to become very damaging in maize agriculture, and the synthetic chemicals employed in maize production considerably reduce the value of the feed and quality of the maize kernels. As a result, it has been suggested that using botanicals as a pest management method may be effective (Badshah et al. 202)]. The uniqueness of plant extracts is their biggest asset because the majority of them are practically harmless and non-pathogenic to both animals and people (Rioba and Stevenson, 2020; Ullah et al. 2022). Various plant species have shown insecticidal properties against autumn armyworm; for example, extracts of neem, Azadirachta indica, Argemone ochroleuca Sweet (Martínez et al. 2017), Boldo, Peumusboldus Molina, Jabuticaba, and Myrciariacauliflora andO. Berg.The research's findings provide sufficient proof that using botanical extracts to treat autumn armyworm has a number of potential applications. Utilisation of these potentials is constrained by a number of operational issues (Mkenda et al. 2015; Mkindi et al. 2020).

CONCLUSION

The damaging insect pest identified as FAW of maize has a significant negative influence on most of the world's regions that grow maize. All of the nations that produce maize in Africa and Asia have been invaded, as well as the United States. The insect's high rates of reproduction and quick dispersal made isolated control measures ineffective in controlling the pest population. Thus, integrating all available tools and techniques is essential for effective pest management in maize. The majority of the earlier research on autumn armyworm management was collected and reviewed in this review paper. According to the research that has been done, it has been found that the environmental conditions affect how the autumn armyworm lives its existence. Significantly, a drop in temperature lengthens the life cycle, and when a hospitable environment is present, the insect can perform 4-6 generations a year. Early kharif planting has always permitted the crop to evade greater levels of infection by managing field conditions. The ability of maize cultivars bred from resistant lines, such as Mp708, FAW7050, Mp708, and FAW7061, to endure outbreaks of autumn armyworm is promising. In addition to these, using cultural, chemical, non-chemical, biological, and biotechnological techniques for pest management as well as seed treatment and intercultural techniques and cropping systems has shown to be good for the sustainable management of FAW with extreme research importance.

Supplementary materials

Andorf, C.; Beavis, W.D.; Hufford, M.; Smith, S.; Suza, W.P.; Wang, K.; Woodhouse, M.; Yu, J.; Lübberstedt, T. Technological advances in maize breeding: Past, present and future. Theor. Appl. Genet. 2019, 132, 817–849

Funding statement

This study was not funded.

Institutional Review Board Statement

The study was approved by the Bioethical Committee of the Department of Agriculture Extension Education, FAE, The Islamia University of Bahawalpur

Informed Consent Statement

Not applicable.

Data Availability Statement

All of the data is included in the article/Supplementary Material.

Acknowledgments

We thank all authors for their Contributions.

AUTHOR CONTRIBUTIONS

All authors contributed equally.

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