



Microbiological resources- an alternate approach for sustainable management of fall armyworm (*Spodoptera frugiperda*)

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Summary

Fall Army Worm (*Spodoptera frugiperda*), with the traits of devastating, voracious, polyphagous nature had recently imposed a global threat. Possessing these traits, this pest constituted a threat to global food security by ambushing more than several host plant species. To tackle this pest, insecticide management approaches was used initially. Later, with a better comprehension of the dynamic biology of the pest, such as their long migration capability, their ability to develop resistance against insecticide and the adverse effects of pesticides on human and the environment, an alternative strategy which is environmentally safe i.e., biological control approaches that is effective and low-risk is laid emphasis. A rich diversity of microbial populations which have the ability to infect the pest to a certain degree in nature remains untapped, and if so, identification of high virulence and productive strains within the population is lacking hitherto. This review focused on the information regarding the scenario of the occurring pest and its damaging nature to the host plants and microbial agents with their surplus potentialities along with the mode of interactions with the insect pest and self-perpetuating nature and their boon of disarming nature. The details of each microbe viz., fungi, bacteria and viruses that possess the traits of controlling the pest naturally are briefed with an insight into molecular information, present findings, constraint and future prospects.

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Introduction

The fall armyworm (FAW), *Spodoptera frugiperda* is a highly polyphagous migratory pest native to tropical and subtropical America, and is reported to attack over 350 hosts across 76 plant families. The essential hosts are maize (*Zea mays* L.), sorghum (*Sorghum bicolor* L.), soybean (*Glycine max* L.), cotton (*Gossypium hirsutum* L.), barley (*Hordeum vulgare* L.), wheat (*Triticum aestivum* L.) (Yang et al. 2019) mostly preferring graminaceous plants (Malo & Hored 2020). The fall armyworm consists of two strains: the "corn strain" mainly damages maize, cotton and sorghum; the "rice-strain" damages rice and other forage grass (Dumas et al. 2015). The maize strain is found to be more prevalent.

The invasive pests mainly disrupt the ecological balance and functioning of other organisms in the new habitat of invasion. It is a transboundary insect with strong flight ability, climate adaptability, and wide host range, enabling it to invade continents through natural distribution capacity and international trade, further posing a threat to food security and livelihoods of the farming community. Studies also state that this pest can travel over 500 km/day before oviposition and 100 km/day in search of the host (Prasanna et al. 2018), due

to which since 2016, *S. frugiperda* has expanded rapidly from America to Africa and Asia. Various climatic factors such as changes in rainfall patterns, increase in O₂ concentrations, and deposition of atmospheric nitrogen affect the growth, development and reproduction of insects, which further determines the distribution patterns (Sun et al. 2021). Although native to America, FAW infestations have spread to India, Nepal, Bangladesh, Sri Lanka, Pakistan, and most of South East Asia. A severe incidence was reported in African countries Siio Tome, Nigeria, and Benin Togo in 2016 (Goergen et al. 2016) and Ghana in 2017 (Cock et al. 2017). By 2018, FAW had invaded Bangladesh and Myanmar, and by January 2019, Thailand, Vietnam (FAO 2018a), Indonesia, Philippines (Lamsal et al. 2020) also reported the incidence. Invasion of FAW also reached Yunnan Province, China, by the end of 2018 (Kalleshwaraswamy et al. 2018; Sun et al. 2021; Konsam et al. 2020). In India, the first report was from Shivamogga district, Karnataka, on 18th May 2018 (Shylesha et al. 2018) and further spread to the neighbouring states of Tamil Nadu, Andhra Pradesh, Telangana, Maharashtra, Madhya Pradesh, Odisha, Bihar, West Bengal, Gujarat, Rajasthan, Kerala, and Uttar Pradesh. By January 2019, the last state to report pest incidence in India was Chhattisgarh.

In the northeast Indian scenario, it was first reported in March 2019 in the Lunglei district of Mizoram and West Tripura district of Tripura state. Massive outbreaks

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with significant damage to maize crops were further detected during April in Mizoram and Nagaland and early May in Meghalaya, Manipur, Sikkim and Arunachal Pradesh states of northeast India. In Manipur, the first incidence of the FAW was reported on 7th May 2019 in Chandanpokpi village of Chandel district, which then invaded all the other districts of Manipur. The

transboundary migration of the pest was suspected from Myanmar via the Chandel district of Manipur bordering Myanmar (Haldhar et al. 2020). Thus, it is also called a “superbug” a need for global early warning by the Food and Agriculture Organization of the United Nations (FAO) for the havoc it creates in worldwide food production (Montezano et al. 2018) (Table 1).

Table 1. FAW severity and loss in global and Indian scenarios

Crop	Location	Crop area Distribution	Severity/loss/ETL	Source
Global Scenario				
Maize	Bangladesh	5.59 lac hectares of land (55.4 lac tons of maize.)	Vegetative stage went up to an estimated 30 to 35%	CIMMYT (2020)
	Bhutan	32,484. 67 acres	90 to 100 per cent	National statistics Bureau, Bhutan (2020)
	Nepal	954158 hectares	371835ha (38.97%)–affected 16.51 %-loss	AICC 2019/20; PQPMC (2021)
	Srilanka	101054 ha	Total infested Extent – 21600 ha	Crop Forecast (2020)
	Ghana	-	US\$284	Day et al. 2017
	Zambia,	-	40%- 124,000 ha	Kansiime et al. 2019
	Malawi	-	9000 ha	Wilson 2017
	Srilanka	101054 ha	Total infested Extent – 21600 ha	Crop Forecast 2020
	Ethiopia	-	32% - 934 kg/ha	Kumela et al. 2018
	Kenya	-	47% (1381 kg/ha)	Kumela et al. 2018
Sorghum	Arkansas, USA	-	1 larva that is greater than 0.5 inches per head	Studebaker 2021
Wheat	Kansas, USA	-	Windowpane injuries are observed in 25–30% of plants	Zukoff et al. 2019
Peanuts	USA	-	FAW exceeds 4/foot within a row and foliage loss exceeds 15%	Studebaker 2021
Soybeans	USA	-	50% defoliation-Prebloom 25% defoliation-Postbloom	Studebaker 2021
Tobacco	Gangachara, Rangpur, Bangladesh	-	11.2% economic damage	CIMMYT 2020
Rice	USA	-	Defoliation exceeds 40%	Studebaker 2021
Indian Scenario				
Maize (estimated area in India- 9.2 million ha)	Karnataka	13.7% of the total area in India	211300 ha	Rakshit et al. 2019
	Telangana	6.1 % of the total area in India	24,288 ha	Rakshit et al. 2019
	Maharashtra	12.0% of the total area	5,144 ha	Rakshit et al. 2019

Since the first report of voracious feeding endemic lepidopteran in America in the year 1797, It is an economic pest of corn and other crops in the Western Hemisphere and is noted for its broad host range (over 80 host plant species reported) and long-distance migration capability (Luginbill 1928). The first invasion was reported in West and Central Africa (Goergen et al. 2016) and later migrated to Sub-saharan and India (Nagoshi et al. 2020). This pest has been spread in more than 109 countries (Kenis et al. 2022). The FAW is a most destructive crop pest, known to attack more than 353 plant species across the globe (CABI 2019). Insecticide application can kill beneficial insects, such as

parasitoid wasps, that mitigate FAW populations (De Lang et al. 2018). Furthermore, FAW has developed resistance to both transgenic *Bt*-maize and chemical insecticides (Ingber et al. 2018). Current EPF's products are focused on the formulation of immature larvae stage. However, the compatibility of EPF's with FAW pheromones and their impact on fertility and egg viability highlight the potential for the development of t and infect application strategies (Akutse et al. 2020). With the increase in the use of chemicals for the management of pests and diseases, there is the development of resistance against chemicals. In such, one can see the development of antibiotic resistance in the daily human

health of superbug. In case of FAW also, it is similar to others. Due to its high migratory and polyphagous in nature, it is very difficult to manage FAW. This review has focused on the present scenario of FAW; its probable alternative management by different microbial resources such as fungal, bacterial and viral are enumerated.

Biology of Fall armyworm

Several studies showed that the egg-hatching rate, larval survival rate, adult oviposition, and emergence rate of Noctuidae insects are affected by humidity levels in the occurring region. (Chen et al. 2001). FAW, a lepidopteran pest, undergoes metamorphosis viz. Egg, larva, Pupa and Adult. The pest takes 30 days and 60 days to complete its life cycle in summer and autumn. However, a prolonged duration of 80 to 90 days is observed during winter.

1. Egg

Females lay egg masses containing 150-200 eggs in two to four layers on the lower part of the leaf (CABI, 2019). Fecundity is about 1500 eggs on an average of 2000 (maximum) (Igyuve et al. 2018).

2. Larva

The larval stage of FAW completes in six instar stages (Igyuve et al. 2018). The young larvae feed on the lower leaves in the initial stages and then ascend onto the corn plant to consume the leaf tissue leaving the veins and midribs in one week (Bohnenblust & Tooker 2012). This implies the most damaging stage in the life cycle of the pest. Thus, it causes a delay in crop development and a decrease in yield (Hernández-Trejo et al. 2018).

3. Pupa

The final stage larva stops feeding and turns greenish to bright brown before pupation (Sharanabasappa et al. 2018). The pupation occurs in the soil (2-8 cm deep) or mature maize ears (reproductive parts) (CABI 2019). The pupal duration lasts 8 to 9 days in summer and 20 to 30 days in the cold season (CABI 2019).

4. Adult

The pre-oviposition period of female moths is 3 to 4 days, after which egg laying is from the first 4 to 5 days of life up to 3 weeks. Adult life lasts about 7 to 21 days, with an average of 10 days (Prasanna et al. 2018).

Application

Sustainable development can be achieved with initial awareness of the pest to the farmers. The management of FAW with suitable technologies and integrated pest management paves the way to control pests and help increased crop production and returns to farmers. On-farm trials (OFTs) can also be conducted to study the strategies for pest control. Cultural practices, mechanical management with the installation of sex pheromone traps, foliar sprays, need-based insecticidal sprays, and microbial biopesticides can be incorporated at varying crop growth stages. Intercropping Maize with non-host crops also minimizes crop loss and curtails the spread of the pest (FAO 2018b). Thus, the early detection of FAW and adoption of appropriate IPM strategies restrict the pest's movement.

Of the management practices, biological control has the most potential for long-term economic, health, and environmental benefits. *In situ* protection of natural

enemies by habitat management, the augmentative release of *Trichogramma pretiosum* or *Telenomus remus* @ 50,000 per acre at weekly intervals or based on trap catch of 3 moths/trap, microbial Biopesticides at 5% damage in the seedling to early whorl stage and 10% ear damage with entomopathogenic fungi and bacteria are beneficial. The FAW larvae, mainly infected with a baculovirus, the dead larvae will be found hanging upside down in the upper parts of the infested maize plant (Prasanna et al. 2018). The important entomopathogens targeting the life stage of FAW are enlisted in Table 2.

Table 2. Some natural pathogenic microbes of fall armyworm

Natural Enemy	Life Stage
<i>Bacillus cereus</i>	Larvae
<i>Bacillus thuringiensis</i>	Larvae
<i>Bacillus thuringiensis alesti</i>	Larvae
<i>Bacillus thuringiensis darmstadiensis</i>	Larvae
<i>Bacillus thuringiensis thuringiensis</i>	Larvae
<i>Bacillus thuringiensis kurstaki</i>	Larvae
<i>Beauveria bassiana</i>	Eggs/Larvae
<i>Granulosis virus</i>	Larvae
<i>Metarhizium anisopliae</i>	Eggs/Larvae
<i>Nucleopolyhedrosis virus</i>	Larvae

Fungal microbes against fall armyworm

Entomopathogenic fungi are diverse organisms that serve a variety of ecological roles. Soil-inhabitant microbes such as *Metarhizium* and *Beauveria* control natural arthropod populations and form complex relationships with plants (Litwin et al. 2020). As they do not produce harmful environmental effects, they are also called "green pesticides" (Sandhu et al. 2017). Bio-pesticide is an environmentally benign substitute for chemical pesticides since it comes from a variety of sources, has a lot of room for improvement, has minimal drug resistance, and has reduced non-target toxicity, including no mammalian toxicity (Walia et al. 2017).

Entomopathogenic fungi are ubiquitous in nature and have shown remarkable effectiveness in the control of insect's epizootic. Natural infection of up to 24% with EPFs has been widely reported on FAW in China (Guo et al. 2020). Natural epizootics have also been documented in Kenya's invaded regions (Gichuhi et al. 2020), India (Shylesha et al. 2018; Sharanabasappa et al. 2019; Firake & Behere 2020a; Ramanujan et al. 2021, Singh et al. 2021) and Indonesia (Ginting et al. 2020a) with up to 79% infection. Furthermore, tackling this invasive pest with native EPF's has been done in Sub-Saharan Africa (Akuts et al. 2019); Thailand (Rajula et al. 2021) with a mortality rate as high as 91.67 %; in China (Idrees et al. 2022) with a significance efficacy in egg larvae and neonate larvae in each respective experiment. Nonetheless, Gutierrez-Cardenas et al. (2019) observed EPF's pathogenicity towards adults and also found that auto-dissemination of EPF's by preparing contaminated male + synthetic pheromones. EPF's used as seed treatment also showed a promising effect (Lestari et al. 2022). *Beauveria bassiana* and *Metarhizium anisoplia* are commonly used

entomopathogenic fungi against fall armyworm with high mortality (Mwamburi et al. 2021). Furthermore, the potentiality of another EPF's *Nomuraea rileyi* where the natural infection is observed has been studied and showed a promising result (Mallapur et al. 2020). *Hirsutella* spp. (1.94%) natural infection on FAW is also recorded in the findings of Lopez et al. (2018).

Pathogenesis of EPF's

Direct cuticle penetration is the principal way of infection by Entomopathogenic fungi. Unlike bacteria or viruses, they do not have to devour it (Bilgo et al. 2018). They are known for the production of cuticle-degrading enzymes and secondary metabolites (Wang et al. 2021). Information on the infection process of EPF on FAW through ultramicroscopy is very meagre and was observed by (Kiruthiga et al. 2022) using SEM where the adherence of the conidia on the head, cuticular ornamentations of the thorax, sensory seta and legs along with formation of germ tube and appresoria with subsequent hyphal colonization. Furthermore, concluded that understanding the fungal–host interactions at the ultramicroscopic levels could reform present tactics for developing hyper-virulent EPF strains. The fungal hyphae begin to proliferate after entering the arthropod's hemocoel. Some EPF have the ability to form blastospores that can colonise the tissues of the host by entering the hemolymph. The fungus at this stage creates secondary metabolites that paralyse and interfere with the physiological functions of the host, primarily its immunological responses (Donzelli & Krasnoff 2016). The growing infection causes the

insect's body to deteriorate due to nutrient deprivation as well as mechanical damage to the internal organs caused by growing hyphae (Fan et al. 2017). Secondary metabolites are numerous low-molecular-weight organic substances secreted by entomopathogenic fungi, especially in reaction to environmental factors. The quantity of chemicals generated shows that they are essential for sustaining the hosts' essential bodily processes as well as for successful infections by weakening their immune systems or neurological systems (Donzelli & Krasnoff 2016). They can be classified into the following categories based on their chemical structure: cyclic depsipeptides (cyclic tetradepsipeptides and cyclic hexadepsipeptides), peptides (octadepsipeptides, dipeptides, and depsipeptides), amino acid derivatives, polyketides, peptide derivatives, and terpenoids (Donzelli and Krasnoff 2016; Wang et al. 2018b) and novel biological compound (Zhang et al. 2020). Mechanism of toxin-insect interaction is also well characterized to some Genus (Wang et al. 2021). However, improvement of EPF's for environmental persistence and virulence is necessary through genetic engineering. Deng et al. (2019b) observed that virulence can be enhanced by recombinant expression of AaIT (Androctonus australis Hector insect toxin) in fungi, an insect-specific neurotoxin (Lovett & St Leger 2018). Also, overexpression of cysteine-free protein gene (endogenous) shows faster kills action, which is analogous of high efficacy (Mou et al. 2022) (Table 3).

Table 3. Virulence genes of EPF's associated for successful infection

EPF	Gene	Phenotype	Source
<i>Metarhizium ansopliae</i>	MAD1 and MAD2	Delay germination, reduced virulence, suppressed blastospore formation and reduced host adherence	Wang and Leger 2007
	Mpl1	Disrupt lipid homeostasis and appresoria formation	Wang and Leger 2007
<i>Beauveria bassiana</i>	Hyd1 and hyd 2	Reduced virulence and reduced host adherence	Zhang et al. 2011b
	Bbhog1	Reduced virulence, conidial yield, host adherence, appressoria and stress-tolerance	Zhang et al. 2009
	Bbcyp52x1	No appressoria, reduced cuticle breaching, host adherence and conidiation	Zhang et al. 2010
	GAS1	Reduced virulence and cuticle penetration	Rajula et al. 2021
<i>Normuraea rileyi</i>	MrMid2	Reduced virulence, conidiation, dimorphic transition, stress tolerance	Xin et al. 2020

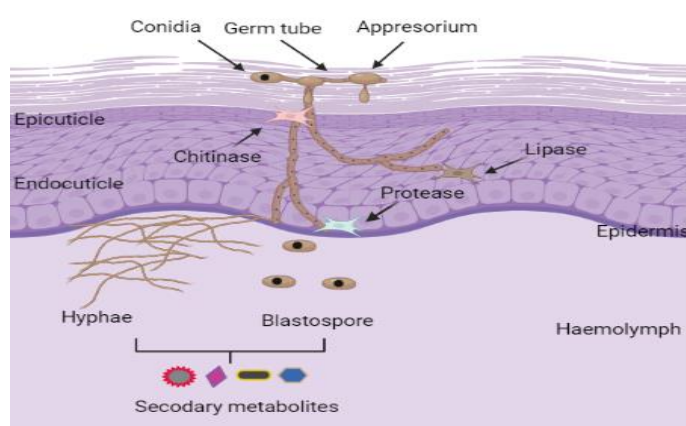


Figure 1. Diagrammatic representation of EPF's pathogenesis

FAW has consolidated their presence, and implementation of chemical to eliminate is not an ideal approach. Therefore, utilizing nature's own system to maintain a healthy ecosystem in controlling one population by another population is the most natural way to tackle insect pest in this era. When conidia come into contact with a susceptible host's cuticular layer, adhesion and germ tube development set off the infection. Then, both the insect pathogen and host cause the production of genes associated to fungal infection structures, hydrolytic enzymes, and host defensive mechanisms. Normal cleavage of the hosts' epidermis is a symptom of a successful fungal infection. The host

body will get colonised when the fungus passes through the developing hyphal and enters the hemolymph. Productions of secondary metabolites (toxins) are crucial in weakening the immune system of the host, harming the muscular system and Malpighian tubule, impairing host excretion, and impairing eating and motility.

Even though great progress have been made fungal biological control agents still needs improvement; such as biopesticide formulations cannot be easily combine with anti-corrosive ingredients, which affect the preservation, environmental conditions affecting the biopesticides which results in unstable efficacy, the price of bio-pesticides is relatively high compared to chemical pesticides, and ultimately to make used of microbial resources to make breakthrough to obtain high virulence and productive strains.

Bacterial adversary to fall armyworm

Entomopathogenic bacteria dominate the world bio pesticides in respect to their eco-friendly nature, production, and persistence and safe handling. The ingestion of these bacteria by the pest leads to the cessation of the pest. Bacteria are in general prokaryotic, unicellular organisms without nuclear membrane and other well defined intracellular membrane enclosed organelles. However, the employment of bacterial pesticides cannot be competitive in relation to employment of synthetic pesticides considering the narrow specificity, spectrum, their survival against the adverse the effects of environment (Table 4).

Table 4. Overview of bacterial pesticides with their mortality rate on FAW

Microbes	Isolate	Experiment	Efficiency	Country	Source
	<i>Bt</i>	<i>In vitro</i>	85.92 (1 st instar larvae) 64.44% (3 rd instar larvae) 50.00% (5 th instar larvae)	India	Helen et al. 2021
<i>Bacillus thuringiensis</i>	AAU strain	<i>In vitro</i>	59.01-64.65%	India	Patel et al. 2020
	KN50, KN11, KNR 68	<i>In vitro</i>	--	China	Liu et al. 2019
	1644, β 44	<i>In vitro</i> Maize leaves	61-87%	China	Liu et al. 2019
	1644, β 44	Artificial diet	7%	Puerto Rico	Viteri et al. 2018
	Dendrolimus HD 37, aizawai HD68, kurstaki HD73, darmstadiensis HD 146, thuringiensis 4412	BOD	HD68: 100%, 4412: 80%	Brazil	Polanczyk et al. 2000

When these bacteria are employed in the FAW infested fields, they first pass to the hemocoel, avoiding FAW's defensive barriers. This paves the way for their extreme proliferation and induces their virulence factors that incur disease and other effects on the host and drag the host to death. These virulence factors are in encoded by the genes that lie in operon regions where their expressions are at rapid rates. Most of the commercially available bacterial pesticides are identified based on the islands of pathogenicity which was acquired by the horizontal gene

transfer that possess the virulence factors that bring death to the host pest when it interacts, whereas in other cases these virulence factors are present on plasmids that gets transferred in the course of conjugation in Bt model (Glare et al. 2017).

1. Action of *Bacillus thuringiensis* on FAW

Bt have a versatile range of activates on insects. It tends to produce a number of virulence factors that are specified to the production of toxins that are synthesised and stored in the cell during the spore formation and

finally to a parasporal crystal. This peculiar trait is used to differentiate this strain of *Bacillus* from other species. The two main toxins from *Bacillus* are Cry and Cyt along with vegetative insecticidal proteins are produced by the vegetative *Bt* cells (Crickmore et al. 2015; Jidung et al. 2022).

When FAW is ingested by FAW these *Bt* enters and targets the midgut epithelial cells that compromise the integrity of the epithelial cells resulting in damage to the epithelium that eventually creates a way to enter the hemocoel. After reaching the hemocoel of FAW, these *Bt* replicates and proliferates their number until the nutritional status at the spot gets depleted to zero levels and then enters the sporulation stage (Raymond et al. 2013).

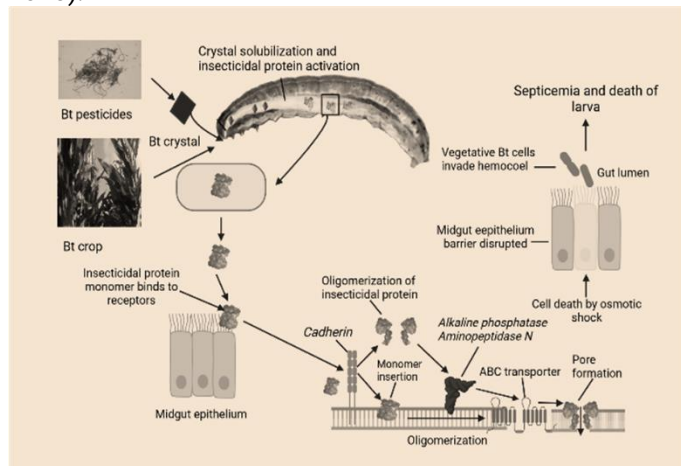


Figure 2. Mode of action of *Bacillus thuringiensis* against FAW

2. Gut microbes for managing fall armyworm

Natural epizootic of SfMNPV (*Spodoptera frugiperda* multiple nucleopolyhedrovirus) has been reported in America (Garcia-Banderas et al. 2020), India (Firake et al. 2020), Indonesia (Ginting et al. 2020b), China (Lei et al. 2020) and Africa (Wennmann et al. 2021). In contrast to the NPV, the granulovirus (genus Betabaculovirus) affects natural populations of FAW less frequently and kills them much more slowly (Pidre et al. 2019). Entomopathogens are becoming more popular as biopesticides against FAW because of their efficiency, minimal mammalian toxicity, and the possibility of being created as low-risk biopesticides for controlling fall armyworm (Popham et al. 2021). Furthermore, some farmers have multiplied viruses at a very local level by infecting larvae with the pathogens gathering them, crush them, strain them, and then apply an extract solution to maize plants that are FAW-infested. Lei et al. (2020) also stated that virus was also collected from the FAW natural population. Response made by many farmers indicates that increased use of synthetic pesticides is not always safe and effective against FAW due to these more sustainable alternatives is needed, such as biopesticides (Bateman et al. 2021) as it can cause insect resurgence in maize, harming maize production and consumption (Kumar et al. 2022). Biopesticides such as microbial and microbial extracts, microbial and semiochemicals can be used in conjunction with crop management as it gives lower risk for pest management

and reduce the amount and need to apply another insecticide (Bateman et al. 2018).

Despite being one of the largest and most commercially significant insect orders, Lepidoptera (butterflies and moths), the ecology and functions of their gut microbiomes sometimes need to be clarified (Jones et al. 2019). Plant defences prevent insect herbivory target the assailant's digestive tract. Plants can play a crucial role in developing bacterial populations that are linked to insect herbivores. The plant defence mechanism against the fall armyworm results in creating a great opportunity for the resident gut microbes to penetrate the protective gut barrier, invading the body cavity. Many defences that plants produce target the insect digestive system, causing collectively to deter and reduce herbivory. Some alter the protective peritrophic matrix (PM) responsible for multiple digestive functions (Mason et al. 2019; 2021).

Virus

Viruses, especially those from the baculovirus group, are a crucial tool and a practical substitute for other biological control agents in integrated pest management framework for pest control of agricultural relevance (IPM) (Hussain et al. 2021).

1. Baculoviruses

Large viruses of the family Baculoviridae have circular dsDNA genomes that range in size from 80 to 180 kbp. The virions are embedded in discrete occlusion bodies that measure 0.15–5 µm and are made up of enclosed, rod-shaped nucleocapsids. The matrix of the occlusion bodies is made up of a single viral protein that is produced in high quantities during infection (Harrison et al. 2018). It is well known that baculoviruses can change the behaviour of their caterpillar hosts by causing hyperactivity (enhanced movement) and/or tree-top disease (climbing to elevated positions before death) (Gasque et al. 2019). Although taking longer to kill the target insect than chemical insecticides, baculoviruses are nevertheless regarded as a vital and potent tool in integrated pest management.

2. Nucleopolyhedron Virus (NPV)

NPV is one of the most used biocontrols against Lepidoptera and infects a wide range of insect pests. They are host-specific pathogens and in susceptible species, they cause lethal epizootic and do not harm non-target species. The presence of a polyhedral-shaped inclusion body in NPV infects the larva and causes infectious lethal disease and infects the gut cell of the larva by spreading to other tissues of the body, which causes death. NPV can be detected easily with light microscopy and they are mainly isolated from the infected insect collected from field. The majority of the infected larvae reduce feeding with less activity which then degraded gradually, dead larva hangs on maize leaves with abdominal prolegs. Larvae turned into pale pinkish during late instars and discharge of body fluid is observed the infected larvae produced orange, brownish liquid discharge and was noticed from the emerging adult and with the help of a microscope (Raghuveer et al. 2019), larvae died within 24 hours (Withers et al. 2022). With the treatment of NPV, a significant decrease in the number of larvae infesting the ear which shows

that new chemistry, including biopesticides are necessary for sustainable control of FAW (Qureshi & Kostyk 2021). SfMNPV is essential to successfully managing local FAW populations (Hussain et al. 2021). Lei et al. (2020) examines the biological and molecular traits of a SfMNPV strain isolated from Chinese maize (SfMNPV-Hub). SfMNPV with superior properties for the control, virus-based pesticides for FAW and utilized effectively to manage *S. frugiperda* (Lei et al. 2020; Popham et al. 2021). In vivo, virulence of baculovirus isolates Sf9 cell cultures tested positive for infection by SfMNPV strains (Zanella et al. 2022; Jidung et al. 2023). Gomez et al. (2022) evaluated *S. frugiperda* by the application of NPV and *M. rileyi* in combination, causing higher mortality compared to biocontrol agents used separately.

3. Granulosis Virus (GV)

The larvae survive for several weeks showing symptoms of infection such as loss of appetite, decrease in mobility, yellowish-white coloration and a swollen larvae body due to the accumulation of occlusion body in the infected tissues with non-raptured integuments after dead (Cuartas-Otalora et al. 2019), Pidre et al. (2019) also observed the same. Mixture of viruses i.e. Granulovirus (SpfrGV) to enhance the infectivity of multiple Nucleo polyhedron virus (SpfrMNPV) was evaluated and showed a significant result as compared to two-fold doses of the latter. (Cuartas-Otalora et al. 2019).

4. Ascoviruses

Viruses having circular dsDNA genomes of 100–200 kbp and oblong encased virions of 200–400 nm are members of the Ascoviridae, family lepidopteran larvae are the major target of ascovirus, which is mechanically transferred by parasitoid wasps, where it can also reproduce (Asgari et al. 2017). The weak oral infectivity of ascoviruses prevents them from being turned as bioinsecticides, despite their potential as competent insect viruses. In formulations with *Heliothis virescens* ascovirus isolates, *Bacillus thuringiensis kurstaki* (Btk) was used as a helper to harm the midgut of lepidopteran larvae (*Helicoverpa armigera*, *Mythimna separata*, *Spodoptera frugiperda*, and *S. litura*) (HvAV-3h and HvAV-3j). Insects of 3rd instar larvae were fed Btk and ascovirus mixture (Btk/HvAV-3h and Btk/HvAV-3j) (Yu et al. 2021). The differences in pathogenicity between related ascovirus isolates, *Heliothis virescens* ascovirus 3i (HvAV-3i) and *Heliothis virescens* ascovirus 3j (HvAV-3j) were used to inoculate four noctuid pest species (*Helicoverpa armigera*, *Mythimna separata*, *Spodoptera frugiperda*, and *Spodoptera litura*), high mortality (over 95%) was caused by the HvAV-3j inoculation in the four examined larval species. Likewise, the four investigated larval species experienced different mortalities following HvAV-3i inoculation than those following HvAV-3j injection (Yang et al. 2022).

Bacillus thuringiensis

A Gram-positive bacteria called *Bacillus thuringiensis* (Bt) creates Cry proteins during the stationary phase, which are protein crystalline inclusions that are encoded by various cry genes and cry genes, such as cryIA, cryIAb, and cryIF, are readily available and have been used for

more than 20 years in commercial Bt maize cultivars all over the world (Padhee & Prasanna 2019). *Bacillus thuringiensis* is the microbial disruptor of insect midgut membranes (Bezuidenhout & Nunkumar 2017). It causes a reduction in larval population (Varshney et al. 2021). *S. frugiperda* are resistant to Bt-maize due to extensive use of the crop, which occurred in many countries. Very high cross-resistance among Cry1 protein was observed, particularly Cry1F (Boaventura et al. 2021) and susceptibility in Vip3A (Boaventura et al. 2021). However, findings by Yang et al. (2017) suggested that Cry2Ab2 can produce significant cross-resistance to Cry2Ae and Bt crops expressing related Bt proteins, but it is not cross-resistant to the Cry1F, Cry1A.105, or Vip3A protein or to maize or cotton plants expressing these Bt proteins. Moscardini et al. (2020) also reported the same with Cry1F, Cry1A.105, and Vip3A20 under field conditions to control *S. frugiperda* in Brazil. Bt makes the Vegetative Insecticidal Proteins (VIP) class of lepidopteran-specific proteins. The vip3A gene, which confers FAW resistance, is the most important of the vip genes that encode these VIPs (Padhee & Prasanna 2019). These Bt maize hybrids provided average protection against FAW that was superior to conventional insecticides, despite the fact that the initial generation of Bt maize technologies accessible in the area was based on the Cry1Ab protein, which has limited effectiveness against FAW. When FAW larvae feed inside the whorl of maize plants, the effectiveness of insecticidal sprays to control FAW is often reduced (Burtet et al. 2017).

Virus associated in the management of fall armyworm

Spodoptera frugiperda (J. E. Smith) (Lepidoptera: Noctuidae) is an economically significant pest species native to the Americas (Sparks et al. 1979). It is a highly polyphagous pest species that feeds on over 350 plant species, including important staple crops like maize, rice, sorghum, and soybean (Montezano et al. 2018). FAW is a significant economic threat to crop production and livelihood, particularly among smallholder farmers in newly encapsulated areas. Many rural farmers in China and other parts of Africa are experiencing decreased profitability in maize production due to the purchase of chemical pesticides to control FAW (Yang et al. 2021). The use of viruses to control FAW is a promising alternative. Some insect viruses are virulent, have a limited host range, and have no negative environmental effects when compared to chemical pesticides (Prasad et al. 2016).

Present Predicament of Viruses under FAW Control

Recent technological advancements have increased the availability of virus products on the market to control a wide range of insect pests worldwide. *Spodoptera frugiperda* multiple nucleopolyhedrovirus (SfMNPV), a baculovirus that infects *S. frugiperda*, has also become commercially available and is currently registered in some countries for *S. frugiperda* control (Haase et al. 2015). Aside from baculoviruses, some other virus species have been discovered in lepidopteran insects, primarily in caterpillar mass rearing or cell culture (lepidopteran cell lines).

1. Ascoviruses

Ascovirus infection causes the formation of virion-containing vesicles in the hemolymph of infected larvae, giving the hemolymph a milky appearance, which is a distinct disease symptom (Table 5) (Federici et al. 2008). The circulation of virions and vesicles in the hemolymph facilitates mechanical transmission of the virus by endoparasitic wasps during oviposition from diseased to healthy larvae or pupae (Federici et al. 2008). Ascoviruses cause chronic to fatal disease in larvae, causing stunted growth, difficulty moulting, and death. In natural populations of *S. frugiperda*, ascovirus infections are found in all larval stages. Despite their high virulence, no records of their use in biological pest control have been found.

2. Baculoviruses

Baculoviruses have a biphasic infection cycle that involves two types of enveloped and rod-shaped nucleocapsids (virions): occlusion-derived viruses (ODVs, which infect the midgut first) and budded viruses (BVs, spread within the insect). Occlusion bodies (OBs; also known as polyhedra) contain the ODVs (Harrison et al. 2012; Ros 2020). The OBs encircle, protect, and stabilise infectious virions against biotic and abiotic factors such as UV light (Harrison et al. 2018; Sajjan et al. 2016). As a result, OBs enable relatively long-term storage and spraying of baculovirus suspensions (Popham et al. 2016). Baculoviruses are classified into two morphological types: NPVs and GV, which differ in the viral protein that makes up the crystalline matrix of the OBs, polyhedrin for NPVs and granulins for GV (Harrison et al. 2012). Baculoviruses have been extensively studied for their biological control (as biopesticides) and biotechnological applications as expression vectors for in vitro protein production and as a delivery vector in mammalian gene therapy studies (Haase et al. 2015; Ros 2020). Baculoviruses and their hosts co-evolved closely, as evidenced by a mostly very narrow host range limited to single or closely related host species (Harrison et al. 2012). In contrast to chemical pesticides, the high specificity allows for targeted and specific insect pest control with no negative impact on humans, the environment, or beneficial insects (Szewczyk et al. 2009). Alpha baculo viruses infecting *Spodoptera* species, such as SfMNPV, *Spodoptera exigua* MNPV (SeMNPV), *Spodoptera littoralis* nucleopolyhedron virus (SpliNPV), and *Spodoptera litura* NPV, have an extremely narrow host range (SpliNPV). Furthermore, the ability of baculoviruses to be used in integrated pest management (IPM) programmes alongside other control agents has made them a highly appealing insect pest control alternative to chemical pesticides. Humans eventually used these properties to use baculoviruses against economically important pests. The majority of baculoviruses cause lethal infections in insects and infect insect larvae (Behle et al. 2012; Cuartas-Otalora et

al. 2019) (Table 5). Furthermore, some baculoviruses alter caterpillar behaviour, such as hyperactivity and climbing to the top of the plant or tree before liquefaction (Gasque et al. 2019). According to AgBiTech2021 and US EPA 2021, SfMNPV is the most used viral candidate in the biological control of *S. frugiperda*. Several SfMNPV isolates are used, some of which cause high *S. frugiperda* larval mortality (Behle et al. 2012). Dead caterpillars are an important source of inoculum for the occurrence and maintenance of epizootics in diseased populations (Haase et al. 2015). Epizootics are desired for biological control because dead caterpillars can help a virus spread to healthy non-infected caterpillars. *S. frugiperda* has been infected by other baculoviruses. Although other baculovirus isolates can be used to control *S. frugiperda*, inter-host effectivity is often low, so obtaining local baculovirus isolates of SfMNPV and/or *Spodoptera frugiperda* granulo virus (SfGV) is critical for effectively controlling local FAW populations.

3. Rhabdoviruses (RNA Virus)

A rhabdovirus (Sf-rhabdovirus) was identified in the *S. frugiperda* Sf9 cell line using next-generation sequencing (NGS) and bioinformatic analyses, making it the first reported rhabdovirus in a lepidopteran cell line (Table 5) (Ma et al. 2014). Sf-rhabdovirus resembles plant rhabdoviruses more than vertebrate or invertebrate rhabdoviruses. Sf-rhabdovirus was discovered infecting Sf9 cells indefinitely, and the virus sequence was also found in a parental Sf cell line, Sf21 (Ma et al. 2014). Recently, the presence of genetically diverse Sf-rhabdovirus isolates in naturally occurring adult *S. frugiperda* populations was discovered (Schroeder et al. 2019). Nonetheless, no study has yet shown the presence of rhabdoviruses in any of the FAW larval stages.

4. Other Virus Families

Other viruses that may infect *S. frugiperda* include DNA viruses such as iridoviruses, entomopoxviruses, densoviruses, and nudiviruses, as well as RNA viruses such as iflaviruses, cypoviruses, tetraviruses, dicistroviruses, and nodaviruses (Chen et al. 2012; Prasad et al. 2016). Some of these viruses have been used successfully in biological pest control programmes against important crops and plants. *Oryctes rhinoceros* nudivirus (OrNV) was used to control the coconut beetle, *O. rhinoceros*, in coconut and oil palm plantations (Bedford et al. 2013; Prasad et al. 2016). In addition, a commercial cypovirus product (Matsukemin®) against the pine moth, *Dendrolimus spectabilis*, has been developed and registered in Japan (Miller et al. 1999). In addition, some densoviruses have been used successfully to control insect pests (Bergoin et al. 1998). However, no naturally occurring *S. frugiperda* infection by these densoviruses has been reported to our knowledge.

Table 5. Some virus families associated with FAW, infection stage and symptoms

Viruses associated with FAW	Virus Name	Infected stage	Main Symptoms	Source
DNA Viruses				
Ascoviruses	<i>Spodoptera frugiperda</i> ascovirus (SfAV-1a)	Larvae	Stunting of infected larvae, production of virus-filled	Federici et al. 2008

			vesicles, milky-white discoloration, fat body cells infection	
Baculoviruses	<i>Spodoptera frugiperda</i> multiple nucleopolyhedrovirus (SfMNPV), <i>Spodoptera frugiperda</i> granulovirus (SfGV), <i>Spodoptera littoralis</i> nucleopolyhedrovirus (SpliNPV)	-	Whitish-grey discoloration, swollen body, ruptured integument leading to liquefaction of the larvae	Haase et al. 2015; Raghunandan et al. 2019
Densoviruses	Junoniacoeniadensovirus (JcDV)	Larvae	Anorexia, lethargy, hypoxia, and inhibition of molting	Eberle et al. 2012
RNA Viruses				
Rhabdoviruses	<i>Spodoptera frugiperda</i> rhabdovirus	Sf9 and Sf21	No described symptoms	Ma et al. 2014
Partiti-like viruses	<i>Spodoptera exempta</i> virus 1, 2, and 3 (SEIV1-3)	Larvae	Reduced the growth rate and fecundity of FAW larvae and increase susceptibility to baculovirus	Xu et al. 2020

Challenges of using baculoviruses for biological control

The willingness of farmers to use viruses to control pests in the field is the main social challenge of using baculoviruses for biological control (Carradore 2019). The willingness varies across geographical regions and socioeconomic groups of farmers (Haase et al. 2015; Carradore 2019). However, some farmers are hesitant to "spray a virus" to control a pest in the field. Furthermore, there may be legitimate concerns about the potential drawbacks of using baculoviruses as biopesticides, such as their high cost in comparison to chemical pesticides (Grzywacz 2017; Lacey et al. 2015) and variable performance in the field (García-Banderas et al. 2020). In addition to the points raised above, farmers may be hesitant due to a lack of understanding of the mode of action and safety of insect-pathogenic viruses and the role viruses play in global pandemics (Carradore 2019). More education about the safety of baculovirus applications is needed for farmers and the general public to increase acceptance of baculovirus technology. The use of baculoviruses for biological control faces both technical and social challenges. One of the technical challenges is that baculoviruses are less effective against target pests than chemical pesticides. Field-derived virus isolates frequently necessitate a higher concentration and take longer to kill pests (Moscardi et al. 1999). Another feature that limits baculovirus efficacy is the susceptibility of their OBs to ultraviolet (UV) radiation, which damages the viral DNA. This reduces their efficacy and half-life in the field. Local and international agricultural institutions, such as the Food and Agriculture Organization (FAO), the Centre for Agriculture and Bioscience International (CABI), the International Institute of Tropical Agriculture (IITA), and the International Centre of Insect Physiology and Ecology (ICIPE), play an important role in creating and increasing awareness of the technology's adoption and acceptance.

Conclusion

In the sight of devastating nature of cultivation crops and its tendency of continuously spared of FAW across the globe and the indiscriminate employment of pesticides

and unpropitious traits of pesticides on the environment should be minimized to achieve a legitimacy. To counteract these falls by the pest, a strategy of biological control that has minimal impact on the environment and requires basic methods for their production is essential. In this regard, microbes' biological control of pests paves the way to maintain the pest population at threshold levels and minimises the losses incurred. To hamper the pest losses, several field trails should still be required to have a glance at these microbes over FAW. To the same extent, different susceptibilities, FAW populations from various geographical origins to versatile microbes to be exposed as the action and production of anti-pesticidal properties differ to the prevailing environment; this stands at a priority to develop a suitable biological control that maintains the pest below the damage incurring levels. Depends on indigenously developed bio-agents have more possibilities and effectiveness in maintaining pest populations. The reasons for this are the microbial agent's inbuilt acquaintance and adaptability nature. In addition to this, the governing bodies of the country and industry sector should promote the knowledge and benefits of using biocontrol agents and make them available to the end users by providing subsidies and other possibilities.

Author's Contribution

Bireswar Sinha, SM Haldhar: Conceptualization, Data organization, Investigation, Writing – original draft. SM Haldhar: Data organization, Kota Chakrapani: Bacteria to FAW, Zarzoliana Ralte: Fungus to FAW, CN Nidhi: Distribution of FAW, Baby Wangkhem: Viruses to FAW, and Jeti Konsam: Re-checking of the original manuscript.

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