Chapter

Role of Microbial Biopesticides as an Alternative to Insecticides in Integrated Pest Management of Cotton Pests

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Abstract

Cotton (*Gossypium hirsutum* L.) is the most produced natural fibre worldwide, and it contributes significantly to the economy of almost 80 cotton-producing countries. Given the high pest infestation, huge amounts of insecticides have been used in cotton production. However, this has resulted in the development of resistance from primary cotton pests and contamination of the environment. Furthermore, the reduction of beneficial insects and outbreaks of secondary pests have been observed. Many arthropod pests are associated with cotton, most of which belong to the orders Lepidoptera, Thysanoptera, and Hemiptera. Biocontrol agents play a critical role in preventing pests in most cotton-growing areas globally. Biological control of cotton pests forms part of integrated pest management as most of these pests have developed resistance against synthetic pesticides. This chapter focuses on the effects of some of the biopesticides, on cotton insect pests. It examines the control of cotton pests using microbial-based products *Bacillus thuringiensis*, *Beauveria bassiana*, *Helicoverpa armigera* nucleopolyhedrovirus and *Metarhizium rileyi*. Furthermore, the chapter summarizes the application of microbial biopesticides as well as the advantages and disadvantages of using these biocontrol agents in agriculture.

Keywords: Cotton, Insecticides, Microbial biopesticides, *Bacillus thuringiensis*, *Beauveria bassiana*, *Metarhizium rileyi*, Nucleopolyhedrovirus

1. Introduction

Pests and diseases are estimated to cause 60% losses in cotton production throughout the world [1]. A successful control strategy requires integrated pest management (IPM) that prevents or suppresses damaging populations of insect pests by applying the comprehensive and coordinated integration of multiple control tactics, including chemical, cultural and biological methodologies.

Synthetic insecticides are mainly used on cotton to control insect pests rapidly [2], and farmers opt for insecticides as the first line of defense [3]. Since the development of synthetic insecticides after World War II, they have been extensively used in agriculture due to their efficiency in pest control and yield increment of many crops [4]. Cotton has been reported to receive more chemical control than most other arable crops [5]. Cotton uses up to 60% of all commercialized agrochemicals globally [6]. Various insect pests and beneficial insects coexist in a cotton ecosystem; however, insecticides have reduced the impact of beneficial insects [7]. As one of the management tools for pests, synthetic insecticides can be used as part of integrated pest management to promote sustainable pest control methods [8]. When synthetic insecticides such as organophosphate (1960s), carbamates (1970s), and pyrethroids (1980s) were introduced, they had an impact on agricultural pest control and resulted in high yields [9].

Although chemical control remains a key method to control targeted pests, a controversy has surfaced regarding the use and abuse of pesticides [9]. The diversity of pests found on cotton requires serious control, mostly with pesticides, which subsequently has a negative impact on natural enemies and the environment [10]. The continuous use of synthetic chemicals to protect crops may also result in resistance to insecticides in pest populations [3]. Combining chemical and biological controls is important for integrated pest management; however, this has not been entirely explored due to, among others, the insufficient information on the insecticide tolerance or resistance of natural enemies [11]. The development of integrated pest management strategies is required to reduce insecticide use and maximize the impact of natural enemies.

Biological control includes introducing a natural enemy or living organisms [12], and cultural control focuses on manipulating the environment to reduce the pest's populations [13]. Pest management has evolved to include integrated pest management that focuses on biological control strategies, including biopesticides. It has been widely reported that chemical pesticides have a negative impact on the environment; therefore, efforts have been made to minimize their use in controlling insect pests. Biopesticides are commonly used to manage agricultural pests through specific biological effects [14] compared to wider control of synthetic pesticides. They contain organisms or substances derived from natural resources in nature and have inhibitory effects on insect pests.

Biopesticides are cheaper, take less time to develop [15], and are naturally less toxic to humans and the environment [16] compared with synthetic pesticides. They are mainly categorized into biochemical, plant, and microbial pesticides [17–19]. Biochemical pesticides include plant extracts, pheromones, plant and insect growth regulators that control pests by non-hazardous mechanisms [20]. Plant pesticides, also known as plant-incorporated protectants, include genetically modified crops using protein from the bacterium *B. thuringiensis* [15]. Microbial pesticides consist of viruses, fungi, and bacteria [21]. Biopesticides form only around 5% of the global pesticides [22], while microbial pesticides account for over 75% worldwide [23]. This chapter provides an overview of microbial-based products *B. thuringiensis*, *B. bassiana*, *H. armigera* nucleopolyhedrovirus, *M. rileyi* and their application to control cotton pests. The chapter further explores the constraints and opportunities for the use of these biopesticides.

2. *Bacillus thuringiensis*

Bacillus thuringiensis (Bacillaceae) is a spore-forming gram-positive bacterium that produces poisonous insecticidal crystal proteins used on more than 3 000 different insects [24, 25]. The bacterium commonly lives in soil, water, plants and dead insects [26]. It was first isolated by Shigetane Ishiwatari in 1901 and first used commercially in the 1920s [27]. *B. thuringiensis* accounts for 95% of the biopesticide market worldwide [28]. The bacterium plays a significant role in biological control because it is the most widely used microbial control agent [19]. Different strains

Control	Findings
Larvicidal activity of *B. thuringiensis* strains against *B. tabaci* [43]	The second instar larvae of *B. tabaci* exhibited mortalities of up to 69%.
Interaction of *B. thuringiensis* and *B. bassiana* for biological control of *B. tabaci* [44]	Higher concentrations of *B. thuringiensis* and *B. bassiana* had above 90% mortality of *B. tabaci* nymphs
Efficacy of *B. thuringiensis* spray applications for the control of *E. biplaga* [45]	*B. thuringiensis* spray provided between 77 and 88% control of *E. biplaga* after ten days
Effects of *B. thuringiensis* on *A. argillacea* and *A. gossypii* of cotton [42]	Dipel® had good control on *A. argillacea,* selective for *A. gossypii,* and caused an increase in cotton yield
Evaluation of *B. thuringiensis* strain when applied to *B. tabaci* nymphs [46]	*B. thuringiensis* strain had 88–92% mortality of the third and fourth instar of *B. tabaci* nymphs
Efficacy of biopesticides and chemical insecticide to control *H. armigera* [47]	*B. thuringiensis* showed the highest mortality rate of *H. armigera* larvae in the shortest period
Efficacy of *B. thuringiensis* against *H. armigera* under laboratory and field conditions [48]	*B. thuringiensis* showed 95–100% and 76% *H. armigera* mortality under laboratory and field conditions, respectively
Influences of *B. thuringiensis* cotton on *A. gossypii* [49]	*B. thuringiensis* cotton efficiently prevented *A. gossypii* resurgence in response to insecticide use
Effects of *B. thuringiensis* on larva and adult of *B. tabaci* [50]	*B. thuringiensis* showed latent effects on the reproductive potential of *B. tabaci*
Evaluation *B. thuringiensis* for control of *Heliothis* spp. on cotton [51]	Dipel® exhibited higher mortality of *Heliothis* spp. larvae

Table 1.
Summary of some studies on the control of cotton pests using Bacillus thuringiensis.

of *B. thuringiensis* have been produced with different spectrums of activity [29]. Although there are massive spectrums with different cry toxin genes, kurstaki and aizawaï are the only two *B. thuringiensis* subspecies developed into products used to control lepidopteran pests [30]. *B. thuringiensis* commonly attacks larval stages of different insects rather than adults or other stages [31, 32]. As a target-specific pathogen, *B. thuringiensis* only attacks the target insects [33] without disturbing non-target insects and natural enemies [32, 34]. *B. thuringiensis* does not kill the target pest on contact but through disruption of the midgut tissue of the insect [31]. Therefore, it is difficult for the pathogen to attack those insects that feed inside the plant [32]. *B. thuringiensis* toxins have shown well-documented toxicity against various insects, including Lepidoptera, Diptera, Hemiptera, Coleoptera, and nematodes [35–40]. In cotton, *B. thuringiensis* has been widely reported as a biopesticide to control various insect pests [27, 41, 42]. **Table 1** provides an overview of some studies conducted to control some cotton pests using *B. thuringiensis*.

3. Beauveria bassiana

Beauveria bassiana (Ascomycota: Cordycipitaceae) is a fungus that grows naturally in soils. It is one of the commercial alternatives to chemical insecticides [52]. Its strains have been used as the active ingredient in several biopesticides to control a diversity of agricultural pests [53]. The genus *Beauveria* contains at least 49 species, of which approximately 22 are considered pathogenic [54]. Notwithstanding its importance as a biological control agent, *B. bassiana* is also an organism used to examine fungal growth and development, such as host-pathogen interactions [55, 56]. Its strains can be developed as host-specific, considering their broad-spectrum as

Control	Findings
The activity of protease and the virulence of *B. bassiana* isolates against *T. urticae* [66]	The isolate of *B. bassiana* caused 15 to 70% mortality of *T. urticae*
Pathogenicity of *B. bassiana* isolates against *H. armigera* larvae [67]	Of 22 *B. bassiana* isolates, four exhibited ˃80% larval mortality
Assessment of the effects of exposure of *H. armigera* larvae to *B. bassiana* [68]	Pre-adult duration of *H. armigera* was extended, and longevity and fecundity were decreased
Effect of isolates of *B. bassiana* against different life stages of *B. tabaci* on cotton [65]	*B. bassiana* isolate had the highest eggs (65.30%) and nymphs (88.82%) mortality
Effect of *B. bassiana* on cotton growth and control of cotton bollworm [54]	*B. bassiana* significantly reduced boll damage, increased plant dry biomass and seed cotton yield
Infection of *H. armigera* by endophytic *B. bassiana* colonizing tomato plants [69]	*B. bassiana* has potential as an effective strategy to control *H. armigera*
Susceptibility of different stages of *T. urticae* to *B. bassiana* in the laboratory [55]	*B. bassiana* gave 90% mortality of *T. urticae*
Effect of *B. bassiana* against *A. gossypii* on cotton [52]	Plants inoculated with *B. bassiana* had significantly lower numbers of *A. gossypii*
Control of *H. armigera* (Hubner) with *B. bassiana* [70]	The highest dose of *B. bassiana* gave 76.7% mortality on the fourth instar larvae of *H. armigera*
Effect of *B. bassiana* on the control of *T. urticae* [58]	*B. bassiana* had 81.8% control of *T. urticae*
Biological control of *T. urticae* [71]	Two strains of *B. bassiana* caused 80% mortality of *T. urticae* in the laboratory and one strain-controlled *T. urticae* in the field

Table 2.
Summary of some studies on the control of cotton pests using Beauveria bassiana.

an insect pathogen [57]. *B. bassiana* has good control by coming into contact with the insect pests [58]. *B. bassiana* attacks its host by penetrating the exoskeleton or cuticle [59], producing a toxin that prevents the immune response of the host [52]. Even though *B. bassiana* based biopesticides may reduce the application of chemical pesticides; their effectiveness requires enhanced formulation or combining them with other pesticides [60]. *B. bassiana* is a promising pathogen against a variety of cotton pests, including spider mites [61], stainers [62], thrips [63], whiteflies [64, 65], aphids and bollworms [52, 54]. Some research on the efficacy of *B. bassiana* on cotton pests are documented in **Table 2**.

4. Metarhizium rileyi

Metarhizium rileyi (Farlow) Kepler S.A. Rehner & Humber (Ascomycota: Clavicipitaceae), formerly known as *Nomuraea rileyi* (Farlow) Samson, is a potential agent for microbial control of insect pests that can cause considerable agricultural productivity loss [72]. *M. rileyi* was firstly described as *Botrytis rileyi* in 1883, then as *Spicaria rileyi* (Charles 1936) and later moved to the genus *Nomuraea* (Kish, Samson, and Allen 1974). In 2014, Kepler, Humber, Bischoff, and Rehner transferred the fungi to the genus *Metarhizium*. It is an entomopathogenic fungus commonly known to infect and cause mortality in insects, particularly the lepidopterans [73–75]. The spores of this fungus penetrate the body of the host through the cuticle or by ingestion when the larvae are feeding. This fungus grows inside the larvae and

Control	Findings
The potential of *M. rileyi* as a biological control agent of *B. tabaci* [86]	*M. rileyi* isolate had a high mortality rate and control efficiency against *B. tabaci*
Field evaluation *N. rileyi* against *H. armigera* [87]	*N. rileyi* significantly reduced *H. armigera* (74.58%) larval population
Effect of *N. rileyi* on *H. armigera* cellular immune responses [85]	*N. rileyi* suppressed the cellular immune response of *H. armigera*
The occurrence of an entomopathogenic fungus on *H. armigera* larvae [84]	The natural occurrence of *N. rileyi* caused 33% of the total mortality of *H. armigera* larvae
The effective dose of *N. rileyi* against *H. armigera* [83]	*N. rileyi* was effective against the developmental stages of *H. armigera*
Bio-efficacy of *N. rileyi* against *H. armigera* [88]	*N. rileyi* revealed 30–83% mortality against different instars of *H. armigera*
The efficiency of *N. rileyi* against *B. tabaci* [89]	The percentage of infested plants with *B. tabaci* significantly decreased after treatments with *N. rileyi* under the field conditions
Comparison of *N. rileyi* with *B. bassiana* and *I. fumosorosea* against *H. armigera* in the laboratory [90]	*N. rileyi* performed the best with a mortality rate of 87 ± 1.4% against *H. armigera*.
Pathogenicity of *N. rileyi* against *H. armigera* larvae [91]	*N. rileyi* showed 73 to 87% mortality of *H. armigera* larvae within eight days
Application of *N. rileyi* for the control of *H. armigera* [92]	*N. rileyi* showed an average of 95% mortality in fourth instar and fifth instar larvae of *H. armigera*
Effects of *N. rileyi* in a field population of *H. armigera* [93]	*N. rileyi* showed higher rates of fungal infection (37%) in *H. armigera* found on pigeon pea

Table 3.
Summary of some studies on the control of cotton pests by using Metarhizium rileyi*.*

reproduces, resulting in internal tissue destruction. The fungus is host-specific and eco-friendly, making it significant in integrated pest management [76]. However, *M. rileyi* has been rarely developed and commercialized [77]. As a result, the host range of *M. rileyi* has been reported to be only around 60 species compared to fungi such as *B. bassiana* [74]. Under favourable environmental conditions, caterpillars from the Noctuidae family are mostly attacked by this pathogen [78].

This fungus is a biological control agent for about 30 species of orders Lepidoptera [79], although two species of order Coleoptera are also found to be susceptible [80]. As a well-known entomopathogenic fungus used in the biological control of pests, limitations such as the long pathogenic process and its application are limited [81]. On the contrary, Jaronski and Mascarin [82] have claimed that *M. rileyi* can be easily produced than other fungi. *M. rileyi* has been broadly studied, mainly on its efficacy against cotton bollworm *H. armigera* [83–85]. **Table 3** presents some research work on the control of cotton pests using *M. rileyi*.

5. Nucleopolyhedrovirus

Baculoviruses belong to the family Baculoviridae, which consists of four genera, including Alphabaculovirus [94]. Viruses from this family have been recorded since 1911, and their natural hosts include almost 700 insect species, mainly belonging to the orders Lepidoptera, Hymenoptera, and Diptera [95]. Baculoviruses are insect-specific [96, 97] and are usually limited to one or a few insect species [98, 99].

Because of their specificity, these viruses can form part of the resistance management strategy [100], demonstrating genetic variations among species [98].

Several members of baculoviruses that display promising results have been successfully developed into commercial biopesticides to control agricultural and forest insect pests worldwide [101]. However, the application of these pesticides has a limited acceptance due to marketing, slow speed of kill, and difficulties with registration and mass production [102]. The production relies mainly on baculoviruses infection and transmission in vulnerable hosts as well as harvesting and purification [103]. Although viruses can be an alternative to synthetic insecticides, they depend on integrating other management strategies [104]. Baculoviruses are part of integrated pest management programmes to control pests in field crops [102]. Despite the regular use of baculoviruses as biopesticides, biological insecticides based on the bacterium *B. thuringiensis* remain the most used biopesticides [94].

Nucleopolyhedrovirus (NPV) is a naturally occurring pathogen that belongs to the group of Alphabaculovirus, and it is a lepidopteran-specific virus [105]. The virus reproduces in the host cells, causing nuclear polyhedrosis disease, and the outbreak of the virus may assist in controlling the host population [106]. The nucleopolyhedrovirus has the potential to control the target insects without harming the environment, pest predators, and parasitoids [107]. *Helicoverpa armigera* nucleopolyhedrovirus (HearNPV) is specifically developed to control *H. armigera,* and the formulations are commercially available throughout the world [108]. The first commercialization of HearNPV was done in China in 1993 [106]. It is reported to have significant potential as a biopesticide in the field [102, 109]. Nucleopolyhedrovirus can be used in conjunction with other insecticides to control

Control	Findings
Assessment of NPV and spinosad against *H. armigera* in a controlled environment [113]	The highest concentrations of NPV had the highest mortality of 95%
Pathogenicity of HearNPV against *H. armigera* [114]	HearNPV had 90–100% mortality effects of newly hatched and second instars larvae
Evaluation of different HearNPV concentrations on neonate, 3rd, and 5th instars larvae of *H. armigera* [115]	The highest dose of HearNPV showed 92% mortality within 14 days
The ability of HearNPV to kill each *H. zea* instar, and a second infestation [108]	HearNPV was successful in controlling early instars of *H. zea* in 5 days
The efficiency of production of HearNPV in *H. armigera* [116]	HearNPV exhibited 80–93% of virus-induced mortality in individualized *H. armigera* larvae
Insecticidal efficacy of HearNPV on *H. armigera* [117]	Larval mortality of *H. armigera* ranged from 97.9–100% at ten days post-application of HearNPV
Efficacy of HearNPV as a control in the cell transfection analysis [118]	HearNPV caused paralysis, weight loss, and suppressed growth and feeding of *H. armigera* larvae
Bio-efficacy of NPV against *H. armigera* [119]	NPV significantly reduced both larval population and boll damage
Field efficacy of (HaNPV) isolates and insecticide control against *H. armigera* on cotton [120]	HaNPV isolates significantly reduced *H. armigera* larvae and recorded the highest yield of over 2 000 kg ha^{-1}
Evaluation of HearNPV for control of *H. armigera* in citrus [109]	HearNPV had a 100% reduction of *H. armigera* larval infestation within 7–16 days

Table 4.
Summary of some studies on the control of cotton pests using nucleopolyhedrovirus.

H. armigera [110, 111]. It is recommended that the application of HearNPV must commence when cotton starts flowering, and the pests are observed in the field [108]. However, the interaction between HearNPV and host insects remains poorly understood [112]. Bolldex™ is one of the commercial labels currently registered as a HearNPV to control *H. armigera* [102]. Below (**Table 4**) is a summary of some studies on the efficacy of the nucleopolyhedrovirus against cotton pests.

6. Application of microbial biopesticides

Majority of biopesticides that show a reduction of pest populations under controlled environments have not succeeded under field conditions [121]. This is due to that, application methods of biopesticides have not been effectively explored. Most of the equipment used to apply biopesticides were developed for synthetic pesticides and are not suitable for biorational agents [122]. The use of application

Microbial	Product name	Target insect	Manufacturer
Bacillus thuringiensis (kurstaki)	Delfin	*Helicoverpa armigera*	Certis
Bacillus thuringiensis (kurstaki)	Dipel	African (American) bollworm	Valent BioSciences
Bacillus thuringiensis (kurstaki)	Javelin	*Helicoverpa armigera* cotton cutworm	Certis
Bacillus thuringiensis (kurstaki)	Biobit	Cotton bollworm	Valent BioSciences
Bacillus thuringiensis (kurstaki)	Condor	Cotton bollworm	Certis
Bacillus thuringiensis (kurstaki)	Crymax	Cotton bollworm	Certis
Bacillus thuringiensis (aizawai)	Florbac	American bollworm	Valent BioSciences
Bacillus thuringiensis (aizawai)	XenTari	Fall armyworm	Valent BioSciences
Beauveria bassiana	Eco-Bb/ Bb-Protec	Whitefly, red spider mite	Andermatt PHP
Beauveria bassiana	BotaniGard	Whiteflies, spider mites, leafhoppers, aphids, thrips	Lam International Corporation
Beauveria bassiana	Mycotrol	Mealybugs, leafhoppers, aphids, thrips, whiteflies	Lam International Corporation
Beauveria bassiana	Broadband	Stink bugs, red spider mites, thrips, whiteflies	BASF
Beauveria bassiana	Naturalis-L	Thrips, whiteflies, red spider mites	Fargro
Metarhizium rileyi	Nomu-Protec	*Helicoverpa armigera*	Andermatt PHP
Nuclear polyhedrosis virus	Heli-cide	*Helicoverpa armigera*	Pest Control India
Nuclear polyhedrosis virus	Bolldex	*Helicoverpa armigera*	Andermatt PHP
Helicoverpa armigera Nucleopolyhedrovirus	Helicovex	*Helicoverpa* species	Andermatt Biocontrol
Helicoverpa armigera Nucleopolyhedrovirus	ViVus	*Helicoverpa armigera*	AgBiTech

Table 5.
Some of the commercially available biopesticides used to control cotton pests.

equipment designed for uniform application of biopesticides such as air-assisted spraying is essential [123]. The design of methods for biopesticide application also relies on the material used and the shape of the crop canopy [124]. Therefore, thorough coverage of all the surfaces reached by a pest is required for effective control. Over and above the correct equipment, precise microbial inoculants are key for a successful biocontrol programme. Microbial biopesticides can be applied in the field as a powder or in a liquid form through seed treatment, root dip, soil or foliar application [125]. Biopesticides must be applied as per the instructions provided in order to apply the correct dosage and the amount of water. As the persistence of biopesticides is an important factor in their efficacy, the timing of application plays a crucial role in pest control. These biocontrol agents tend to be less effective when applied during hotter day times and high rainfall.

Therefore, applications may be were administered late afternoon due to the UV sensitivity of the biological agents [25]. Alternatively, ultraviolet (UV) absorbents or protectants are necessary to combat this degradation and protect the microbes from sunlight. The UV absorbents or protectants dissolves in the insect stomach and release the virus that kills the pest [126]. However, more commercial UV-resistant biopesticides need to be improved to be readily accepted by farmers. It is also important to carefully select a biopesticide specific for the pests that have to be controlled. Furthermore, the level of toxin in the selected biopesticide as well as the feeding behaviour of the target pest is essential to determine the efficacy of the product [127]. Some of the common trade names for commercially available microbial biopesticides are listed in **Table 5**, and many small manufacturers distribute similar biopesticides using different trade names.

7. Challenges and opportunities for the use of biopesticides

Over-reliance on chemical control results in changes in the status of cotton pests and environmental pollution [7]. There are still challenges to sustain the environment for cotton production [128]. Much research has focused on advancing pest control, and biological control agents are an important criterion for sustainable agriculture [129, 130]. Biopesticides or biological pesticides are an eco-friendly alternative to chemical pesticides [131]. They can play a significant role in the integrated pest management of many insect pests [132]. They are obtained from the environment to control agricultural diseases and insects [15]. They are only about 5% of the total crop protection market; however, they are expected to surpass synthetic pesticides by 2050 [133]. The production of biopesticides is sometimes highly labour intensive and difficult to produce at levels that are economically viable and profitable [134]. Enhancement of biopesticides has been explored by improving different compounds to sustain their efficacy as well as the shelf life [135, 136]. The development of non-toxic and effective biopesticides requires a holistic approach, which will turn most of the research results into profitable business products. Although this section provides generalities, each biopesticide needs to be individually assessed to determine its impacts on pest control, humans, the environment, and other factors associated with the adoption by farmers. The adoption of biopesticides by farmers relies on their efficacy, increased yield, lower prices, and an efficient supply [137]. They have been unreliable and very costly due to their limited market share [138]. However, Sharma et al. [107] reported that bacterial biopesticides are the most widely used and less expensive than other control measures. Biopesticides benefit the farmers due to target specificity, the ability to manage the pest rather than eradicate, and conservation of environmental balance [131]. The very high specificity of the products might be a disadvantage when a complex pest species needs to be controlled. Baculovirus-based insecticides have been considered safe on non-target organisms and can be used as part of integrated pest management to ease the risks of synthetic insecticides [99]. However, baculoviruses are reported to act slowly in killing the targeted pests [60], which has led to the development of faster killing products through genetic modifications [94, 102]. Baculoviruses are also reported to be less effective due to their high susceptibility to ultraviolet radiation, and this requires the reapplication of the virus over time [139, 140]. This effectively increases input costs that farmers may incur. The activity of nucleopolyhedrovirus has been found to decrease significantly over time after applying the virus on the plant leaves [116]. When exposed to direct sunlight, nucleopolyhedrovirus has been reported to be inactivated within a day or two [141]. *B. thuringiensis* has a vast spectrum of insecticidal activity compared to other bacteria, and it is safe for the environment and humans [142]. *B. thuringiensis* does not affect non-target organisms, except for some closely related insects to the target pests [143]. The application of *B. thuringiensis* as a biopesticide is potent and biodegradable than synthetic insecticides [144]. However, the bacterium is effective when the present part of the plant that the target insect feeds on and when larvae are still early instars [144].

The efficiency of entomopathogens mainly relies on their ability to infect the target insect and their persistence [145]. Microbial insecticides have low persistence in the environment, and they require accurate application because many of these pathogens are insect-specific [33]. Namasivayam and Vidyasankar [130] recorded that various formulations of *M. rileyi* are persistent under different temperatures. They further recommended that using bio gel formulation of *M. rileyi* might play a role in controlling pests under field conditions. However, Edelstein et al. [146] reported that this pathogen is extremely sensitive to nutritional and environmental conditions, affecting the virulence of the asexual reproductive spore of fungi and stability in storage [147]. Further research is required to stabilize *M. rileyi* in storage and determine the insecticidal activity of formulated conidia [148]. The persistence of *B. bassiana* under field conditions is negatively affected due to ultraviolet light, extreme temperatures and rain [58]. Sandhu et al. [149] have reported that this pathogen can live longer at lower temperatures and relative humidity. Bouslama et al. [150] demonstrated that some formulations of *B. thuringiensis* could be persistent after rain wash compared to treatment with an unformulated bacterium. Biopesticides that degrade rapidly in the environment may have a short field persistence resulting in numerous product applications [60]. The major constraints of biopesticides are limited to, among others, environmental conditions such as solar ultraviolet radiation, temperature, humidity and their ability on spreading on the surface [145, 151]. Since biopesticides often contain living material, the products have reduced shelf life. Temperature, moisture or humidity also plays a role in the shelf life of the biopesticides [152]. Due to their practical limitations, such as rapidly washing away in rain and degradation by the sunlight, biopesticides may not be as effective as synthetic pesticides. The impact of rain on the persistence of entomopathogenic fungi is less when the conidia are in direct contact with the cuticle of leaves and larvae [153]. Under natural conditions, biopesticides often cause natural mortalities of insect populations [149]. Inglis et al. [154] noted that the influence of rain has a minimal effect on *B. bassiana* persistence; however, high rains washed away significant quantities of *B. bassiana* from leaves. *B. thuringiensis* is reported to persist for few days after application due to weather, UV light, chemical environment and the presence of proteinases [144]. Like the other biopesticides, most spores are washed off into the soil.

8. Conclusion

All cotton pests have the potential to cause enormous damage to the crop if left uncontrolled. Structurally integrated pest management is essential to control the existing or new infestation of pests. Although the use of biocontrol agents on cotton does not eliminate pest populations, their application is crucial to suppress the infestations. Therefore, it is essential to acquire and study pest-related information to make appropriate decisions regarding which control methods to implement. The advantage of using biopesticides rather than complete reliance on synthetic pesticides is that these biocontrol agents are cheaper, target-specific, effective in very small quantities, reduce pesticide resistance, environmental and human friendly. Biocontrol agents must not be regarded as a substitute for synthetic insecticides; therefore, to realize the advantage of using biocontrol agents, integration with other crop protection strategies in the IPM programme is necessary.

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Conflict of interest

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