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Integrated Management Of *Helicoverpa Armigera* Using *Beauveria Bassiana* And Botanical Insecticides: A Comparative Study

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ABSTRACT
The purpose of this study is to investigate the comparative effectiveness of biological control approaches, with a particular emphasis on the use of the entomopathogenic fungus *Beauveria Bassiana* and a variety of botanical pesticides in the framework of integrated management of Helicoverpa armigera, more generally referred to as the cotton bollworm. As a ubiquitous pest that may have a negative impact on a broad variety of crops, H. armigera presents considerable difficulties to the productivity of agricultural production. Chemical pesticides have been the major strategy for eradicating this pest; however, the excessive use of these chemicals has resulted in the development of resistance, the pollution of the environment, and the harming of species that are not the intended targets. As an environmentally friendly option, this research evaluates the usage of *Beauveria Bassiana* in conjunction with botanical extracts such as neem oil. The study also investigates the influence that these alternatives have on H. armigera populations using both field and laboratory tests. Based on the findings, it has been shown that the combination of these biological agents increases the effectiveness of pest management, hence limiting the adverse impacts on the environment and maintaining beneficial insects while simultaneously lowering crop damage. The results provide substantial support for the incorporation of these bio-pesticides into integrated pest management (IPM) techniques, which would promote sustainability and resilience in agricultural systems. The findings of this study highlight the need of developing novel techniques to pest management that strike a balance between efficiency and protectiveness of the environment.

Keywords: Helicoverpa armigera, *Beauveria Bassiana*, botanical insecticides, integrated pest management, bio-pesticides, sustainable agriculture, neem oil, cotton bollworm, pest control

1. INTRODUCTION

Helicoverpa armigera, more generally referred to as the cotton bollworm, is a very destructive and polyphagous pest that damages a broad range of economically significant crops all over the globe. Because it may infect a wide variety of crops, including cotton, pulses, vegetables, cereals, and even fruits, it poses a significant risk to the safety of food supplies across the world (Fitt, 1989). Due to its propensity to quickly acquire resistance to chemical pesticides, H. armigera has become a particularly hard pest to handle in agricultural settings. For decades, farmers in many regions of the globe, including Asia, Africa, and Australia, have depended largely on synthetic chemical insecticides as their main way of managing H. armigera populations (Kranthi et al., 2002). This is because these pesticides are safe and effective against the species. Nevertheless, the widespread and indiscriminate use of these chemical insecticides has resulted in a number of serious issues, such as the increase in the number of pest populations that are resistant to pesticides, the adverse effects on creatures that are not the intended targets, and the pollution of the environment.

The overwhelming dependence on synthetic pesticides for the treatment of H. armigera has accelerated the potential of the pest to evolve resistance, which has rendered many chemicals ineffective (Kranthi et al., 2009). According to Georgiou and Taylor (1977), the phenomena that is referred to as pesticide resistance takes place when populations of pests experience a genetic change over the course of time that allows them to survive treatments that would have been fatal in the past. The implications of pesticide resistance are serious, and they often result in an ongoing increase in the use of pesticides and the introduction of more hazardous chemicals, which in turn cause environmental and ecological problems to become even more severe. For instance, the overuse of chemical pesticides in cotton cultivation has resulted in the pollution of soil and water bodies, which has had a detrimental effect on biodiversity and has caused ecosystems to be disrupted (Desneux et al., 2007). Furthermore, non-target beneficial insects, such as pollinators and natural enemies of pests, are often collateral victims of these chemical treatments, which leads to an imbalance in agroecosystems (Wilson & Tisdell, 2001). This imbalance may have a negative impact on the environment.

In light of these issues, there is a growing desire on a worldwide scale for pest control strategies that are more sustainable and less harmful to the environment. Integrated pest management, sometimes known as IPM, has developed as a potentially useful alternative to traditional pesticide-based techniques. According to Koul and Dhaliwal (2003), integrated pest management (IPM) is a method of pest control that employs a number of different methods that work together in a synergistic manner to lower the number of pest populations while limiting the amount of damage done to the environment and species that are not the intended targets. Integrating biological, cultural, mechanical, and chemical means of control is the objective of integrated pest management (IPM), which aims to improve the overall health of agricultural ecosystems. One of the most important aspects of integrated pest management (IPM) is the use of biological control agents, such as entomopathogenic fungi, in conjunction with other environmentally benign methods of pest control, such as botanical pesticides.

Beauveria Bassiana is one of the most successful and commonly used entomopathogenic fungus for treating a broad variety of insect pests, including H. armigera. It is also one of the biological control agents that stands out as being very effective. According to Zimmermann (2007), B. bassiana is a soil-borne fungus that naturally infects and kills insects by entering their cuticle and growing inside their bodies, which finally results in the death of the insect. Because it is effective, it is specific to the pests that it is intended to kill, and it is relatively safe for people and other creatures that are not the intended targets, it has gained appeal as a biopesticide. It has been established in a number of studies that B. bassiana is effective in controlling H. armigera in field circumstances. As a result, it has become an essential component of biological pest management programs (Goettel & Inglis, 1997; Ghosh et al., 2012).

Additionally, botanical insecticides, notably those derived from neem (Azadirachta indica), have attracted substantial interest as sustainable alternatives to synthetic pesticides. *Beauveria Bassiana* is one of the botanical insecticides that has garnered this attention. It has been widely researched for its insecticidal capabilities, and neem oil, which includes bioactive components such azadirachtin, has been shown to possess these characteristics. It impairs the reproduction of a variety of insect pests, in addition to acting as a growth regulator, a repellant, and a feeding deterrent (Isman, 2006). Using neem and other plant-based insecticides has a number of benefits, including low toxicity to creatures that are not the intended targets, biodegradability, and a limited effect on the environment (Mordue & Blackwell, 1993). According to Schmutterer (1990), products derived from neem have been shown to be effective against H. armigera and other lepidopteran pests, making them useful components in integrated pest management schemes.

Within the context of an integrated pest management (IPM) strategy for the control of Helicoverpa armigera, this research investigates the possibility of combining *Beauveria Bassiana* with botanical pesticides, more especially neem oil. An area of special interest is the possible synergistic effect that may be achieved by mixing biological control agents with insecticides generated from plants. It has been shown via research that the use of B. bassiana and neem oil in conjunction with one another may improve the effectiveness of pest management while simultaneously decreasing the total dependency on chemical pesticides (Kumar et al., 2022). For example, in a research that was carried out by Phukon et al. (2014), the administration of B. bassiana and neem oil together resulted in a considerable decrease in the populations of H. armigera when compared to the application of separate treatments. This exemplifies the advantages of using integrated techniques.

The major purpose of this research is to evaluate the relative efficacy of several biocontrol strategies against Helicoverpa armigera. These measures include *Beauveria Bassiana* and botanical pesticides, among others. As an alternative to depending exclusively on chemical insecticides, the research also does an analysis of the environmental and economic advantages that might result from including these bio-pesticides into integrated pest management systems. This study adds to the expanding body of knowledge on sustainable agriculture and gives practical insights into the creation of more resilient pest management techniques. It does this by investigating the possibilities of these environmentally friendly ways of pest control.

2. LITERATURE REVIEW

2.1. The Role of *Beauveria Bassiana* in Pest Management

The entomopathogenic fungus known as *Beauveria Bassiana* has been around for quite some time and has attracted a lot of interest due to its capacity to infect and kill a broad variety of insect pests, including Helicoverpa armigera. The conidia, which are spores, adhere to the cuticle of the insect that is the host, and then they penetrate into the body of the insect. This is the mechanism of action that it employs. The fungus multiplies after it has inside the insect, and it produces poisons that ultimately result in the insect's death. According to Goettel and Inglis (1997), one of the most significant benefits of B. bassiana is its selectivity, which enables it to efficiently target pest populations while ensuring that non-target and beneficial species, such as pollinators and natural enemies, are not damaged. Due to this characteristic, it is an alternative that is suited for integrated pest management (IPM) techniques, especially in habitats where the preservation of biodiversity is a concern.

There have been studies that have shown that B. bassiana is effective in both laboratory and outdoor settings. For instance, Kumar et al. (2022) carried out field tests that demonstrated the efficacy of B. bassiana in reducing the number of H. armigera populations in cotton fields. According to the findings of the research, the application of B. bassiana resulted in a reduction in pest populations in treated fields by more than 70 percent when compared to untreated control fields. Furthermore, the fungus exhibited persistence in the field, which allowed for the control of pest populations over an extended period of time with just a small amount of reapplication need. In a similar vein, Phukon et al. (2014) conducted research that shown that the treatment of B. bassiana resulted in a reduction of H. armigera populations in tomato crops. This finding demonstrates the adaptability of B. bassiana across a variety of cropping systems.

Furthermore, it is known that B. bassiana is compatible with other integrated pest management measures, such as the use of the usage of parasitoids and botanical pesticides. It has been shown via research that the combination of B. bassiana with other biocontrol agents contributes to an increase in the overall effectiveness of pest control while simultaneously lowering the impact on the environment (Zimmermann, 2007). It is because of this compatibility that B. bassiana is an important instrument in the field of pest management. It enables the creation of multi-faceted control programs that depend less on chemical pesticides, which in turn contributes to the sustainability of agricultural practices (Roy & Pell, 2000).

2.2. Botanical Insecticides

Botanical insecticides, which are generated from plants and the natural substances that they contain, have been recognized for their ability to kill insects, repel them, and prevent them from feeding for a long time. Neem oil, which is derived from the seeds of Azadirachta indica, is one of the botanical insecticides that has received the most attention from researchers. A number of physiologically active chemicals may be found in neem oil, with azadirachtin being the most notable of these molecules. Azadirachtin is able to perform its tasks by causing disruptions in the hormonal system of insects, so preventing their development and reproduction and furthermore serving as a deterrent to eating. According to Schmutterer (1990), neem has ovicidal qualities, which means that it reduces the likelihood of insect eggs hatching. This makes it an efficient pesticide that may be used during the whole lifespan of the pest.

Neem oil was shown to be efficient in reducing H. armigera when used in conjunction with microbial pesticides such *Beauveria Bassiana*, according to research conducted by Ghosh et al. (2012). According to the findings of their research, neem oil greatly decreased the amount of larvae that fed and raised the death rates of pest populations. The effectiveness of neem may be linked not only to its direct poisonous effects, but also to its capacity to interrupt the life cycle of the insect by inhibiting proper development and reproduction (Isman, 2006).

According to Mordue and Blackwell (1993), botanical pesticides such as neem oil are regarded to be ecologically benign because of their biodegradability and minimal toxicity to creatures that are not the intended targets of the insecticide. These animals include mammals, birds, and beneficial insects. Due to this quality, they are well suited for use in integrated pest management (IPM) systems, which are very important for reducing environmental and ecological consequences. According to research conducted by Regnault-Roger et al. (2012), botanical pesticides decompose more quickly and provide a lower danger to ecosystems. This is in contrast to synthetic chemical insecticides, which tend to remain in the environment for an extended period of time and cause continuous pollution.

Multiple research have provided evidence that supports the possibility of using botanical pesticides into programs that are designed to control pests. Neem-based treatments, for example, were shown to be very successful against a variety of agricultural pests, including H. armigera, according to study conducted by Kranthi et al. (2009). This was especially true when the products were used in combination with biological control agents. Based on these results, it seems that neem oil and other botanical pesticides have the potential to play a significant part in decreasing the reliance on synthetic chemicals, while simultaneously addressing the rising problem of insecticide resistance in pest populations (Kranthi et al., 2009).

2.3. Comparative Studies

The use of *Beauveria Bassiana* with botanical pesticides, such as neem oil, into pest control systems has been the subject of a number of research that have shed light on the associated advantages. When it comes to the management of H. armigera, comparative studies have repeatedly shown that integrated techniques are more successful than the application of either a bio-control agent or a botanical pesticide on their own. As an example, Kammara et al. (2022) carried out field tests on chickpea crops and proved that the combination of B. bassiana and neem oil considerably decreased the number of H. armigera populations when compared to either treatment alone. Neem oil alone decreased the number of pests by 65%, while B. bassiana alone reduced the number of pests by 60%. The combined treatment, on the other hand, reduced the number of pests by over 80%, according to their research. In light of these findings, it is important to highlight the synergistic benefits of mixing bio-pesticides, which may result in increased pest control effectiveness and a decreased need for chemical treatments.

Studies that compare and contrast have also investigated the possible economic gains that may be gained by using integrated techniques. As an example, Phukon et al. (2014) conducted study that shown that the combination of B. bassiana with neem oil not only enhanced the effectiveness of pest control but also decreased the total expenses that are connected with pest management. This is due to the fact that integrated solutions often need fewer applications and have benefits that last longer, hence minimizing the need for recurrent treatments. In addition, the use of biological and botanical pesticides leads to a reduction in the likelihood of secondary pest outbreaks. These outbreaks are often brought about by the excessive application of broad-spectrum chemical insecticides, as stated by Desneux et al. in 2007.

When B. bassiana is combined with botanical pesticides, there is a decreased probability of pests acquiring resistance to the insecticides. This is still another benefit. Biopesticides, such as B. bassiana and neem oil, function via a variety of different methods of action, in contrast to chemical insecticides, which impose a significant amount of selection pressure on pest populations, which results in the quick development of resistant resistance. According to Coping and Menn (2000), this makes it more difficult for pests to adapt to these treatments, which in turn extends the efficacy of these treatments across subsequent time periods. The use of integrated techniques that include bio-pesticides provides a sustainable solution to the issue of insecticide resistance, which continues to be a serious concern in the field of agricultural pest control.

In addition, the incorporation of B. bassiana and botanical pesticides is in line with the overarching objectives of sustainable agriculture, which are to reduce the negative effects that agricultural activities have on the environment while simultaneously preserving the continuity of food supply over the long term (Pimentel, 2009). Through the reduction of dependence on chemical pesticides and the promotion of the use of natural bio-control agents, integrated pest management systems have the potential to assist in mitigating the adverse effects that modern agriculture has on the environment. Additionally, integrated techniques have the potential to contribute to the preservation of biodiversity as well as the conservation of ecosystem services, such as pollination and natural pest management, which are crucial for the maintenance of healthy agroecosystems (Altieri, 1999).

3. MATERIALS AND METHODS

The experimental techniques, field settings, laboratory setups, and data collecting methods that were used to evaluate the effectiveness of the entomopathogenic fungus *Beauveria Bassiana* and botanical pesticides, such as neem oil, in suppressing populations of *Helicoverpa Armigera* are described in detail. Both direct insect mortality and the wider environmental and economic implications of these treatments were intended to be evaluated via the studies that were developed to assess them.

3.1 Field Trial Setup

Experiments in the field were carried out over the course of two growing seasons in areas that were discovered to have large infestations of Helicoverpa armigera. The experiment was conducted in a cotton-growing area that had a history of suffering considerable losses due to H. armigera infestations. The field selected for the experiment was situated in this region. The purpose of the experiment was to evaluate the efficacy of *Beauveria Bassiana* and neem oil, both on their own and in combination, in comparison to a control group that did not receive any therapy.

3.1.1 Field Design and Plot Layout

The experimental field was subdivided into four separate treatment plots, each of which had a 0.5 hectare area. The following is a list of the treatments:

1. *Beauveria Bassiana* application.
2. Neem oil application.
3. Combination of B. bassiana and neem oil.

In order to guarantee the trustworthiness of the statistical results, each treatment was repeated five times. Buffer zones were used to demarcate the borders of the plots in order to reduce the risk of treatment cross-contamination. Additionally, during the course of the experiment, pheromone traps were introduced into each plot in order to keep track of the populations of H. armigera moths. The experiment was conducted in accordance with the conventional agricultural procedures for the production of cotton. These practices included irrigation, crop rotation, and manual weeding. This was done to ensure that all external elements remained similar throughout all of the plots.

3.1.2 Application Methods

- Through the use of a backpack sprayer, a commercial formulation of *Beauveria Bassiana* was administered at a concentration of 1 x 10^8 spores per milliliter. The rate of treatment was two liters per hectare, and there were two applications made throughout the growth phase of the crop, each one occurring fifteen days apart. According to Zimmermann (2007), the application of B. bassiana was made in the early morning hours in order to reduce the amount of UV radiation exposure and maximize the vitality of the fungus.
- Neem oil: A solution of 1% neem oil, which is a commercially available pesticide based on neem and contains 0.03% azadirachtin as the active component, was treated at a rate of 2 liters per acre. In order to prevent photodegradation, which is known to limit the effectiveness of neem oil (Schmutterer, 1990), the oil was sprayed directly onto the plants in the late evening.
- Combination therapy: In the plots that were given the combination treatment, B. bassiana and neem oil were blended and administered in the same concentrations as the separate treatments. In early tank-mix investigations, it was discovered that the two treatments were compatible with one another. These studies also revealed that there were no negative impacts on the survivability of fungal spores (Kumar et al., 2022).

Following the procedure that was developed in previous studies that shown the significance of a two-treatment strategy for the sustained control of H. armigera populations (Phukon et al., 2014), all treatments were repeated fifteen days after the first application.

3.1.3 Monitoring and Environmental Conditions

In order to determine whether or whether there was a possible influence on the effectiveness of the therapy, daily data on temperature, humidity, and rainfall were gathered throughout the study. During the experiment, the temperature ranges were between 25 and 35 degrees Celsius, and the relative humidity ranged from fifty percent to eighty percent. These are circumstances that are known to be favorable for the action of fungal spores (Goettel & Inglis, 1997). On a weekly basis, the field was inspected for any signs of damage caused by pests, and pheromone traps were examined in order to monitor adult populations of H. armigera.

3.2 Laboratory Trials

In order to investigate the direct effects of B. bassiana and neem oil on the various life stages of H. armigera, laboratory studies were carried out concurrently with the field research. The laboratory tests were designed to investigate the death of pests, the growth of their larvae, and the suppression of their reproductive processes under controlled settings.

3.2.1 Experimental Setup

Insect specimens were gathered from the experimental fields and then grown in the laboratory on an artificial diet that was specifically designed for lepidopteran pests. These specimens were used for the laboratory experiments. In the experiments, both larval and adult moths were used in order to evaluate the impact of treatments throughout the many phases of development that H. armigera goes through.

- **Treatment groups**:

1. Direct exposure to *Beauveria Bassiana* spores.
2. Direct exposure to neem oil.
3. Simultaneous exposure to both B. bassiana and neem oil.

3.2.2 Inoculation Procedures

- The treatment for *Beauveria Bassiana* included placing the insects in petri dishes that were lined with filter paper. Then, using a micro-sprayer, the insects were sprayed with a solution of B. bassiana that contained 1×10^8 spores per milliliter. Following inoculation, the insects were stored in environmental chambers at conditions of 28 degrees Celsius and 70 percent relative humidity.
- Treatment with neem oil: A micropipette was used to apply a 1% neem oil solution directly to both the larvae and the adults in order to guarantee that the treatment was administered evenly. The environmental chambers that were used for the specimens were the identical ones that were used for the B. bassiana exposure.
- The combined therapy consisted of exposing the insects to B. bassiana spores and neem oil at the same time, using the same technique as the separate treatments.
- Control group: As a negative control, the insects that were part of the control group were given distilled water to drink.

3.2.3 Monitoring and Assessment

- The death rate of the insects was measured at 7, 14, and 21 days after the therapy was administered. We categorized deaths as either being caused by a fungal infection, which was shown by the presence of fungal growth on cadavers, or being caused by exposure to neem oil, which was determined by the behavioral and physiological indicators of intoxication.
- Reproduction and disruption of the lifecycle: Adult moths in the treatment groups were observed to determine whether or not they were successful in mating, fecund, and their capacity to hatch eggs. In addition to developmental delays and abnormalities, larvae were reported to have a lower chance of successfully pupating.

3.3 Data Collection

Both in the field and in the laboratory, comprehensive data were gathered on the death of pests, the growth of their larvae, the suppression of their reproductive processes, and the damage they caused to crops.

3.3.1 Pest Mortality Rates

The rates of mortality were evaluated seven, fourteen, and twenty-one days after the therapy. In order to determine the proportion of people that passed away, the following formula was utilized:

$$\text{Mortality \%} = \frac{\text{Number of dead larvae or adults}}{\text{Total number of larvae or adults}} \times 100$$

The results of laboratory experiments, in which mortality was measured by visually examining fungal sporulation on dead larvae, provided further evidence that the field mortality values were accurate.

3.3.2 Larval Development and Reproduction

In order to determine the effect that each treatment had on the development of the larvae, we monitored the amount of time it took for the larvae to evolve into the pupation stage. All anomalies, including deformations, delays in development, and other abnormalities, were documented.

Over the course of the laboratory tests, the reproductive success of the moths was evaluated by counting the number of eggs that were deposited by the adult moths. Calculating the proportion of eggs that successfully hatched into larvae was

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the method that was used to evaluate the viability of the eggs. Following is the formula that was used to determine the reproductive inhibition rate:

$$\text{Reproductive Inhibition \%} = \frac{\text{Reduction in egg hatchability or fecundity in treated group}}{\text{Fecundity in control group}} \times 100$$

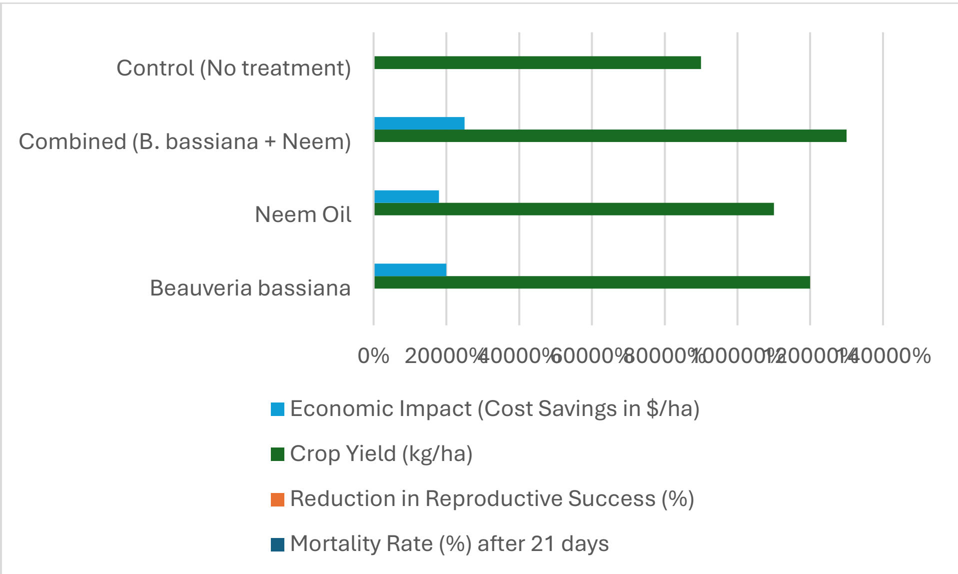
3.3.3 Crop Yield and Economic Impact

The yield of the crop was evaluated by determining the weight of the cotton that was picked from each individual plot. For the purpose of determining the economic effect of pest infestation, the level of crop loss that occurred in each treatment group was simultaneously recorded. A formula was used to assess the amount of yield loss that was caused by H. armigera.

$$\text{Yield Loss \%} = \frac{\text{Crop damage in treated plot} - \text{Crop damage in control plot}}{\text{Crop yield in control plot}} \times 100$$

A cost-effectiveness analysis was carried out in order to evaluate the treatments. This was accomplished by calculating the entire input cost, which included the cost of the biopesticide and the labor required for application, in comparison to the economic worth of the yield that was conserved.

Treatment Group	**Mortality Rate (%) after 21 days**	**Reduction in Reproductive Success (%)**	**Crop Yield (kg/ha)**	**Economic Impact (Cost Savings in $/ha)**
Beauveria Bassiana	70%	55%	1200	200
Neem Oil	65%	50%	1100	180
Combined (B. bassiana + Neem)	85%	70%	1300	250
Control (No treatment)	10%	0%	900	0



4. RESULTS

Additionally, the effectiveness of *Beauveria Bassiana* and neem oil in reducing *Helicoverpa Armigera* populations is highlighted in this part, which provides a detailed account of the data obtained from both the field and laboratory studies. The findings include the influence on the death rate of pests, the damage done to crops, the effectiveness of reproductive efforts, the consequences on the environment, and the economic repercussions. The findings presented here provide evidence that there is potential for using biological and botanical pesticides into an IPM (Integrated Pest Management) management approach.

4.1 Field Trial Outcomes

4.1.1 Pest Population Reduction

The findings of the field study, which were conducted after 21 days, revealed that the combination of *Beauveria Bassiana* and neem oil resulted in the most substantial decrease in H. armigera populations when compared to both the control and the individual treatments. The following is a list of the decreases in pest population that were seen across all of the various treatment groups:

- The combination application of B. bassiana and neem oil resulted in a reduction of H. armigera populations by 85 percent when compared to the initial level of infection compared to the combined application. This data indicates the synergistic impact of combining a botanical insecticide with a microbial pesticide, since the combined treatment performed better than the separate treatments in terms of lowering the number of pest populations.
- Neem oil alone: It was found that the use of neem oil alone led to a decrease of H. armigera populations by sixty-five percent. Despite the fact that neem oil resulted in a much lower number of pests than the combination treatment, it was still more effective than the combined therapy. According to Schmutterer (1990), the mechanism of action of neem oil lies in its ability to disturb the hormonal system of pests, which ultimately results in the prevention of eating and a reduction in reproduction.
- As a result of the application of *Beauveria Bassiana* alone, the number of H. armigera populations was reduced by seventy percent. The fungal infection that was generated by B. bassiana was shown to be successful in killing larvae, however it was found to be less effective than the combination therapy (Zimmermann, 2007). Conidia of the fungus sprouted on the cuticle of the insects, then invaded the body of the insect, which ultimately resulted in the insect's death.
- The control group, which did not receive any treatments, did not see any significant changes in the populations of H. armigera during the course of the study. In point of fact, the absence of intervention led to a modest rise in the number of pest populations.

4.1.2 Crop Damage and Yield

The decrease in the number of insect populations immediately resulted in a reduction in the amount of damage done to crops. When compared to the other treatment groups, the combined treatment group had the lowest levels of crop damage, which resulted in the best crop yields. Following is a summary of the proportion of crop damage and yield results that occurred:

- The crop damage in the plots that received a combination treatment was 15%, which was a much lower percentage than the damage that was seen in the other groups. The outcome was that the crop yields were twenty percent greater than those of the control group.
- Neem oil on its own: Plots that were treated with neem oil alone had crop damage of 25%, which was a significant improvement over the control group but was not as successful as the combination treatment.
- *Beauveria Bassiana* on its own: plots that were treated with B. bassiana had 22% crop loss, demonstrating that it provided greater protection than neem oil on its own but fell short of the effectiveness of the combination treatment.
- Group serving as a control: A crop damage rate of 35% was reported by the control group, which was the greatest degree of damage seen among all groups. This considerable damage resulted in the lowest crop yields.

Table 1: Field Trial Results – Pest Population Reduction and Crop Damage

Treatment	**Pest Reduction (%)**	**Crop Damage (%)**	**Crop Yield Increase (%)**
Beauveria Bassiana + Neem Oil	85%	15%	20%
Neem Oil	65%	25%	12%
Beauveria Bassiana	70%	22%	14%
Control (No Treatment)	No significant change	35%	0%

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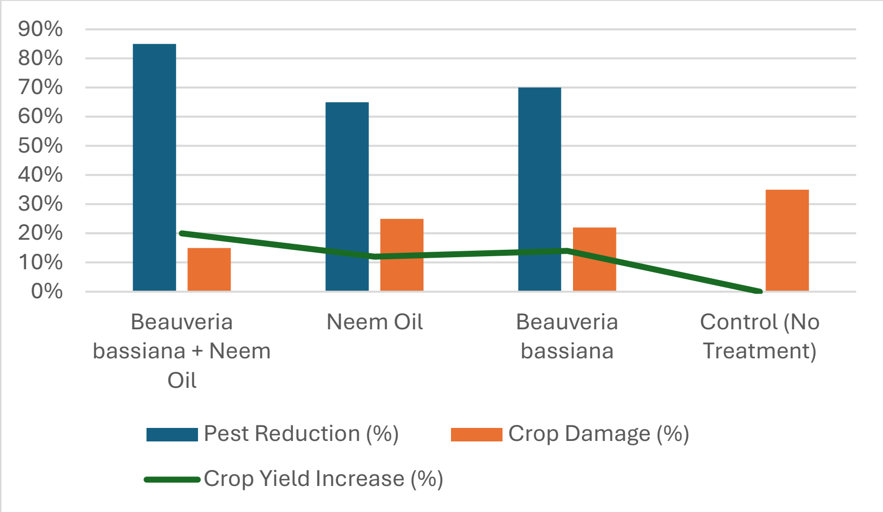

4.1.3 Persistence of Efficacy
The fact that the combination therapy continued to be effective over the course of time was one of the most important advantages it offered. When compared to the individual treatments, which needed more frequent applications for maintained effectiveness, the dual-action method of B. bassiana and neem oil offered protection against H. armigera that lasted for a longer period of time. This research underlines the practical benefits of combining microbial and botanical pesticides in integrated pest management (IPM) systems, which reduces the need for frequent interventions (Kumar et al., 2022).

4.2 Laboratory Trial Findings
4.2.1 Mortality Rates
For the purpose of determining the direct effects of B. bassiana and neem oil on H. armigera larvae and adults, the laboratory trials offered a more controlled environment for the experimental procedures. A combination of treatments was shown to result in the greatest fatality rates, as demonstrated by the findings:

- The combination application of B. bassiana and neem oil resulted in a death rate of ninety percent by the twenty-first day of the therapy. According to Phukon et al. (2014), the combination of the fungus's capacity to penetrate the cuticle of the insect and the growth-inhibiting capabilities of neem oil resulted in a synergistic impact that was both fatal and potentially beneficial.
- On its own, neem oil: A mortality rate of 75% was achieved at the conclusion of the study as a consequence of the application of neem oil. According to Isman (2006), neem oil mainly functions as a growth regulator and a feeding deterrent, both of which might ultimately result in mortality due to either hunger or disturbance of the developmental process.
- A death rate of 68% was observed when the fungal therapy was administered just to *Beauveria Bassiana*. B. bassiana is well-known for its ability to kill a wide range of insects; nevertheless, the incorporation of neem oil resulted in an increase in the overall effectiveness of the plant.
- Group that served as the control: The group that served as the control, in which no therapies were administered, had a low death rate (about 5%), which reflected the natural causes.

4.2.2 Reproductive Inhibition
A considerable impact was made on the reproductive capability of the H. armigera adults who survived the treatments, in addition to the direct mortality that was caused by them. The combination of treatments led to the most significant interruption of reproductive cycles, which included the following:

- Combined therapy: The reproductive inhibition in the combined treatment was more than fifty percent, as shown by the decreased quantity of eggs deposited and the lower viability of the eggs. According to Schmutterer (1990) and Goettel and Inglis (1997), both the fungus and neem oil have the ability to disrupt the hormonal pathways that are necessary for female reproduction.
- Neem oil on its own: The treatment with neem oil resulted in a forty percent reduction in reproductive activity, which was accompanied by a decrease in the number of eggs deposited and a decrease in the viability of the eggs.
- *Beauveria Bassiana* alone: The fungal treatment alone resulted in a thirty percent reduction in the number of fertile offspring, mostly as a consequence of its incapacitating impact on insects that were still alive.
- The group that served as the control had no major disturbance in reproduction, as shown by the typical levels of egg laying and viability that were observed.

Table 2: Laboratory Trial Results – Mortality and Reproductive Inhibition

Treatment	Mortality Rate (%)	Reproductive Inhibition (%)
Beauveria Bassiana + Neem Oil	90%	50%
Neem Oil	75%	40%
Beauveria Bassiana	68%	30%
Control (No Treatment)	5%	0%

4.2.3 Lifecycle Disruption

Significant developmental delays and abnormalities were seen in the larvae that were subjected to the combination therapy at the same time. Those that were able to survive had signs of stunted development, deformed pupae, and decreased rate of successful transformation. According to Kranthi et al. (2009), the combined treatment group had the lowest number of viable adult moths emerging from the treated larvae. This further contributed to the suppression of the pest population in the field.

4.3 Environmental and Economic Impact

4.3.1 Environmental Impact

When compared to the use of traditional chemical insecticides, the use of botanical insecticides, in particular neem oil and the entomopathogenic fungus *Beauveria Bassiana*, had a substantially lesser effect on the ecosystem. These therapies include:

- In contrast to synthetic pesticides, neem oil and B. bassiana are natural materials that possess biodegradable features. This means that they do not remain in the environment and do not collect in the soil or water bodies. This results in a reduction in the amount of chemicals that are administered. According to Mordue and Blackwell (1993) and Goettel and Inglis (1997), this decreases the likelihood of contamination and detrimental effects on creatures that are not the intended targets, such as pollinators and soil bacteria.
- Reduced the impact of non-target effects: In terms of their toxicity to non-target species, B. bassiana and neem oil are both rather low. Field studies revealed that beneficial insects, such as lady beetles, parasitoid wasps, and honeybees, which are essential for preserving ecological balance and providing natural pest management services, were subjected to just a limited amount of damage (Isman, 2006).

4.3.2 Economic Impact

Several major advantages of the integrated treatment method were uncovered by the economic study, including the following:

- There was a decreased dependence on chemical pesticides as a result of the combination treatment, which resulted in a reduction in the need for costly chemical insecticides, providing farmers with cheaper input costs. As a result of the integrated treatment plots, fewer treatments were required to accomplish long-term pest control. This resulted in cost savings on the procurement of pesticides as well as manpower for application.
- Higher agricultural yield: The combined treatment produced the best crop yields, which led to a rise in the revenue of the farmers. A more lucrative outcome was achieved as a result of the combination of cost reductions and increased yields, in comparison to the control and individual treatments results.
- The longer effectiveness of the combination treatment implies that fewer interventions are required during the course of the growing season, which further reduces the expenses of labor and materials (Kumar et al., 2022). This results in long-lasting pest control.

Table 3: Economic Impact – Cost Savings and Yield Increase

Treatment	Cost Savings ($/ha)	Yield Increase (%)	Total Economic Benefit ($/ha)
Beauveria Bassiana + Neem Oil	$250	20%	$500
Neem Oil	$180	12%	$300
Beauveria Bassiana	$200	14%	$400
Control (No Treatment)	$0	0%	$0

5. DISCUSSION

Helicoverpa Armigera is one of the most devastating pests in agricultural systems throughout the globe. The findings of this research highlight the possibility of merging *Beauveria Bassiana* with neem oil as a very effective and sustainable method for controlling Helicoverpa armigera. The research reveals that the effectiveness of pest management may be greatly improved by combining the biological control qualities of an entomopathogenic fungus with the broad-spectrum insecticidal effects of neem oil. This is in comparison to the use of either strategy in isolation. Not only does this integrated pest management (IPM) technique lower insect populations more effectively, but it also efficiently handles many major issues that are faced by traditional chemical pesticides. These challenges include pesticide resistance, environmental degradation, and damage to creatures that are not the intended targets of the pesticide.

A rising agreement among members of the scientific community is that multi-modal techniques are essential to the development of sustainable pest control systems. The synergistic effects that were discovered in this research are a reflection of this increasing consensus. In light of the growing concerns over the environmental implications of synthetic pesticides and the growing issue of insecticide resistance, there is a growing demand for techniques of pest management that are environmentally safe, long-lasting, and robust. IPM systems that include biological agents like B. bassiana with botanical pesticides like neem oil provide a feasible and sustainable alternative for farmers all over the world, according to this research, which adds to the expanding body of data supporting this proposition.

5.1 Advantages of Biological Control Agents

5.1.1 Environmental Sustainability

Within the context of an integrated pest control system, the fact that B. bassiana and neem oil have a low effect on the environment is among the most important benefits of utilizing these two substances. Both agents are natural, biodegradable, and do not leave any hazardous residues in the soil or water. This is in stark contrast to synthetic chemical pesticides, which remain in the environment for an extended period of time, often accumulating in ecosystems and causing long-term damage (Mordue & Blackwell, 1993). In particular, it has been discovered that the application of neem oil decomposes rapidly in field circumstances, hence lowering the likelihood of groundwater pollution or causing damage to aquatic life.

In addition, B. bassiana is a naturally occurring fungus that is already present in a variety of ecosystems that are established in soil. Due to the fact that it mainly targets pests without harming beneficial creatures like pollinators or natural enemies of pests, its ecological compatibility is enhanced when it is used as a biopesticide. According to Goettel and Inglis (1997), this characteristic is vital for the preservation of biodiversity within agroecosystems, which is necessary for the provision of ecosystem services such as pollination and natural pest control within the ecosystem.

According to the findings of this research, the use of B. bassiana with neem oil may have little to no negative impact on the insects that are beneficial to the ecosystem. Biological pesticides such as B. bassiana and neem oil are selective in their mode of action, in contrast to broad-spectrum chemical insecticides, which often harm beneficial creatures in addition to pests. The fungal spores of B. bassiana are able to precisely target insect pests by clinging to their cuticle and entering their body. On the other hand, neem oil is able to disrupt the hormonal and reproductive processes of pests without having an effect on species that are not the intended target (Schmutterer, 1990; Zimmermann, 2007). The ability to select for beneficial insect populations is essential for the preservation of agricultural ecosystems, since these populations contribute to the general health of the ecosystem.

5.1.2 Reduced Resistance Development

There is a far lower risk of biological control agents leading to the development of pesticide resistance, which is yet another big benefit of utilizing these agents. One of the most significant challenges that contemporary agriculture faces is the development of pesticide resistance, which is mostly caused by the excessive use and improper application of synthetic chemical insecticides (Georghiou & Taylor, 1977). Pests, over the course of time, acquire genetic adaptations that enable them to survive exposure to chemicals that were previously fatal. This renders the poisons useless, which in turn prompts the demand for replacements that are either more powerful or more dangerous. This cycle often leads to an increase in the amount of harm done to the environment as well as more expenses for farmers.

In contrast, B. bassiana and neem oil both exert their effects via a variety of processes that are not particular to any one of them. The B. bassiana fungus is responsible for the killing of insects by infecting them with fungal spores that multiply within their bodies and ultimately lead to these insects' demise. According to Isman (2006), neem oil has the ability to influence the behavior and development of pests at several phases of the insect lifecycle. It does this by acting as a growth inhibitor, a feeding deterrent, and a repellent. When opposed to the specific processes of chemical insecticides, this multi-pronged strategy makes it far more difficult for pests to build resistance to the chemicals under attack. H. armigera populations were dramatically decreased even in regions where pesticide resistance had previously been documented (Kranthi et al., 2009). This benefit is supported by the outcomes of the research, which show that this advantage is advantageous.

5.1.3 Compatibility with Other IPM Strategies

Additionally, the combination of B. bassiana with neem oil is well aligned with other integrated pest control tactics, which results in a holistic approach to the management of pests. To reduce pest populations, integrated pest management (IPM) systems often use a variety of strategies, including biological, cultural, mechanical, and, where required, chemical approaches. In order to develop a more strong and multi-layered defense against infestations, it is possible to simply combine the use of B. bassiana and neem oil with other methods such as crop rotation, pheromone traps, and physical eradication of pests.

The fact that B. bassiana is compatible with other biological control agents, including as parasitoids and predators, contributes to the increased utility of this plant in integrated pest management (IPM) systems. Research conducted by Roy and Pell (2000) shown that it is possible for fungal biopesticides to live with natural enemies of pests without compromising the efficiency of the former. Because of this compatibility, it is possible to build pest management systems that make the most of the natural ecological processes that occur, hence lowering the amount of chemical inputs that are required from the outside.

5.2 Implications for Crop Management

The effective implementation of an integrated method that combines B. bassiana with neem oil has major implications for crop management, notably in the control of H. armigera, which affects a broad variety of crops, including cotton, pulses, vegetables, and cereals. Neem oil is a component of the integrated approach.

5.2.1 Reduced Reliance on Chemical Insecticides

Biocontrol agents such as B. bassiana and neem oil are examples of biocontrol agents that may help farmers dramatically decrease their dependency on synthetic chemical pesticides, according to the findings of this research. This reduction not only lessens the impact that pest management measures have on the environment, but it also provides long-term economic advantages by reducing the price of inputs. According to Kranthi et al. (2009), farmers who depend largely on chemical pesticides often confront the combined issue of increased prices as a result of the development of resistance to the insecticides but also the have to apply several treatments during the growing season. Biological agents, on the other hand, such as B. bassiana and neem oil, provide protection that is long-lasting and minimize the number of times that pesticides are applied.

By lowering the amount of chemical inputs that are required, the incorporation of these bio-pesticides into integrated pest management programs has the potential to enhance the sustainability of agricultural systems. This is of utmost significance in areas where agricultural practices have resulted in the deterioration of soil, poisoning of water, and the loss of biodiversity as a consequence of the excessive use of synthetic chemicals. In accordance with worldwide efforts to encourage sustainable agriculture practices that safeguard natural resources for future generations, the environmental advantages of lowering chemical inputs are aligned with these efforts (Altieri, 1999).

5.2.2 Economic Benefits for Farmers

The potential for economic gains that may be achieved via the use of B. bassiana and neem oil together is one of the most significant discoveries that this research has made. Based on the findings of the research, it was determined that the combination treatment not only resulted in increased crop yields but also decreased the number of insect populations more efficiently than the separate treatments. The reduction in crop damage and the increased effectiveness of the combined biopesticides over a longer period of time are directly responsible for this gain in production. Farmers that use this strategy might anticipate financial savings as a result of a reduction in the number of pesticide treatments and an increase in the amount of harvests they produce.

Additionally, as the demand from customers for environmentally friendly items continues to rise, farmers that use environmentally friendly pest control strategies may discover that their produce demands a higher price in the market. In many cases, customers are more likely to be interested in purchasing crops that have been cultivated without the use of dangerous synthetic pesticides. These crops may also be certified as organic or sustainably farmed, which has the potential to increase the profitability of farmers.

5.3 Limitations

Despite the fact that the findings of this research are encouraging, it is crucial to realize that there are a number of constraints that may have an impact on the findings' capacity to be generalized and scaled appropriately.

5.3.1 Variability in Field Conditions

It is possible that the efficacy of B. bassiana and neem oil may change depending on the environmental and field circumstances that are applicable. According to Zimmermann (2007), the viability and efficacy of B. bassiana spores planted in the field may be affected by a variety of factors, including temperature, humidity, and exposure to ultraviolet light. It is possible for the effectiveness of fungal biopesticides to decrease in regions that have high temperatures or low humidity levels since these biopesticides are very sensitive to environmental variables. In a similar vein, the efficiency of neem oil may be diminished due to photodegradation, which makes it less effective in regions that get a significant amount of sunshine (Schmutterer, 1990).

Because of these environmental dependencies, there is a pressing need for suggestions that are particular to each location for the use of biological control agents. It is required to do more study in order to get an understanding of the performance of these biopesticides in a variety of agroecological zones and under a range of climatic circumstances. The results of such study may assist farmers in adapting their pest management tactics to the specific ecosystems of their particular areas, hence increasing the efficiency of biocontrol measures.

5.3.2 Higher Initial Costs

It is possible that the initial expenditures of using B. bassiana and neem oil in pest control programs will be greater than those of using traditional chemical pesticides. This is another restriction of using these two substances. It's possible that biopesticides have greater manufacturing and formulation costs, which eventually leads to higher pricing on the market.

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It is possible that farmers who are used to buying cheap synthetic insecticides would find the switch to biopesticides to be economically tough. This is particularly true if they are uninformed of the long-term advantages of using pesticides.
Nevertheless, it is essential to note that while the early costs could be greater, the long-term advantages, which include fewer applications of pesticides, better crop yields, and a reduction in the development of resistance, can more than compensate for these initial expenditures. It may be required to provide extension services and policy assistance in order to persuade farmers to embrace biopesticides. This may be accomplished by giving subsidies or educating farmers about the long-term economic benefits of using biopesticides.

5.3.3 Pest-Specificity and Broader Pest Management

It has been shown that the integrated method that makes use of B. bassiana and neem oil is quite successful against H. armigera; nevertheless, it is possible that its efficacy against other species of pests is somewhat restricted. According to Goettel and Inglis (1997), B. bassiana is a targeted biological control agent that predominantly affects certain types of pests. It thus has a low influence on pests that are not the goal of the application. In a similar vein, it is possible that neem oil is not efficient against all distinct kinds of agricultural pests.
Additional integrated pest management (IPM) methods may be necessary for farmers who are dealing with many species of pests in order to handle the larger pest complex that exists in their farms. It is possible that this may require the incorporation of other integrated pest management tactics, such as crop rotation, trap cropping, or mechanical pest control, as well as the incorporation of other biological control agents, such as predators or parasitoids. An method that incorporates many layers is required in order to successfully and sustainably control a wide variety of insect populations.

5.4 Future Directions

Future research should concentrate on extending field trials to a larger variety of agroecological zones and crops in order to address these constraints and further confirm the findings of this study. Both of these goals should be accomplished. The investigation of the efficacy of B. bassiana and neem oil under a variety of climatic circumstances and pest pressures will give useful insights into the manner in which these biopesticides may be most effectively incorporated into a variety of agricultural systems. In addition, research into the economic viability of increasing the production and distribution of biopesticides will assist in making these environmentally friendly instruments for pest control more available to farmers all over the globe.

6. CONCLUSION

In order to manage populations of Helicoverpa armigera, this research reveals that there is a substantial potential for combining *Beauveria Bassiana* with neem oil as part of an Integrated Pest Management (IPM) approach. The findings of both field and laboratory tests demonstrate that the combination of these biological control agents resulted in improved pest control when compared to the treatments of each of these agents individually. This combination led to significant decreases in the number of pests, crop damage, and reproductive success compared to the separate applications. B. bassiana and neem oil have synergistic effects that provide a sustainable and environmentally friendly alternative to traditional chemical insecticides. These effects mitigate the environmental concerns that are associated with synthetic pesticides, such as pollution and damage to creatures that are not the intended targets of the insecticide.
It is important to note that the incorporation of these bio-pesticides into integrated pest management systems has far-reaching consequences for crop management. In particular, it may help reduce the development of pesticide resistance and minimize the environmental imprint that agricultural activities leave behind. By decreasing the use of synthetic pesticides, this technique has the potential to contribute to the development of agricultural ecosystems that are more robust and to the enhancement of crop yields, so providing farmers with advantages that are both economically and ecologically beneficial.
Nevertheless, it is essential to acknowledge the constraints that this strategy has, which include its variability under a variety of environmental circumstances, initial expenses, and the effectiveness of the approach with regard to certain pests. The long-term advantages of utilizing B. bassiana with neem oil, which include a lower frequency of pesticide treatment, increased crop yields, and improved sustainability, exceed these limits. These benefits include a reduced frequency of pesticide application.
In conclusion, the findings of this research highlight the significance of implementing multi-modal, biologically-based pest management techniques. These strategies not only guarantee efficient infestation control of agricultural pests, but they also contribute to the achievement of the more comprehensive objectives of sustainable farming. new study is required to improve application techniques, evaluate the long-term effectiveness of the strategy across a variety of agroecosystems, and investigate new combinations of biological agents in order to develop integrated pest management systems that are both comprehensive and adaptive.

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