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Reduced Pesticide Use in Cotton Fields through Biological Control and Companion Planting Strategies

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Abstract The reliance on pesticides in cotton cultivation has long been closely linked to environmental degradation and pesticide resistance in pests, thus necessitating the exploration of sustainable alternatives for pest management. This study reviews current research on reducing pesticide use in cotton agro-ecosystems through biological control and associated planting strategies. It analyzes the main pests affecting cotton yield and quality, highlights the limitations of chemical control, and analyzes methods for natural pest control using biological agents such as *Beauveria bassiana* and Trichogramma wasps. Furthermore, it explores how associated planting can enhance biodiversity and pest control through ecological interactions, supplemented by field case studies from India, Africa, and Australia. By integrating these measures into the integrated pest management (IPM) framework, this study emphasizes their synergistic potential for achieving sustainable cotton production. The combination of biological control and associated planting can not only reduce pesticide dependence but also improve ecological resilience, farmer income, and social well-being, while calling for further research into large-scale implementation and supporting policy frameworks.
Keywords Cotton cultivation; Biological control; Companion planting; Integrated pest management; Sustainable agriculture

1 Introduction

The significance of cotton needs no elaboration. This crop supports a large number of global textile industries. However, behind its high yield, pesticides have always been indispensable. In the early years, chemical pesticides almost became the "standard equipment" in cotton fields. They did indeed ensure stable and high cotton yields, but the cost came at a cost: the ecosystem was disrupted, pest resistance increased, and some previously insignificant minor pests reappeared (Cheng and Zhang, 2025). Water pollution, the decline of beneficial insects, and risks to human health - these problems emerged one after another later on.

For a long time, cotton cultivation has almost become a "disaster area" of pesticide consumption. Despite continuous technological improvements in control measures, old problems such as high-yield losses, the spread of drug resistance, and the emergence of new pest populations remain persistent. Especially in some cotton-producing areas, although the area is not large, the amount of pesticides used accounts for half of the national or even global total. The advent of genetically modified cotton (such as Bt cotton) was once highly anticipated. It did significantly reduce the use of pesticides, but it was not a panacea. The new problem of ineffectiveness against certain pests and the gradual emergence of resistance has plunged farmers into a new predicament (Coupe and Capel, 2016; Trapero et al., 2016).

People have begun to realize that the more pesticides they use, the more they rely on them. Environmental deterioration is only one aspect. The deeper pressure comes from the economic and social levels: medicines are more expensive, less effective, and workers' health issues are receiving increasing attention. As a result, from policies to the public, the calls for "reducing drug use" have grown stronger and stronger. Integrated pest management (IPM), biological control, associated planting, intercropping systems and other methods are beginning to be re-examined. They can suppress pests through natural regulation and restore ecological balance, which is also in line with the development direction of sustainable agriculture (Yi and Ueno, 2024).

Against this backdrop, this study aims to view the issue of pest management in cotton from a different perspective. It does not continue to discuss the old topic of "spraying more or less", but rather starts from biological control and associated cultivation to see if there is a more reliable path to take. First, we will sort out the ecological and agronomic logic behind these two methods, and then combine field experiments with some actual cases to see how they perform in real environments. Finally, we will also discuss the possible difficulties that may be encountered during the promotion process, such as limitations in terms of cost, technology, and cognition, and attempt to propose some feasible improvement directions. Overall, what this research aims to do is not to offer a perfect answer, but to provide a realistic and implementable thinking framework for cotton to move towards a more sustainable production method.

2 Pest Dynamics in Cotton Agroecosystems

2.1 Key pest species in cotton fields

In the cotton field, pests have hardly ever truly left since the day of sowing. The most common ones are still the old rivals of Lepidoptera, Hemiptera and Lanceoptera. The cotton bollworm genus (*Helicoverpa* spp.) is the most representative pest among them. They burrow into cotton bolls, bite off flower buds and directly destroy the yield. Sucking pests, such as *Bemisia tabaci*, *Amrasca biguttula*, aphids and *Thrips tabaci*, although not necessarily damaging tissues, However, by sucking SAP and spreading viruses, the cotton plants gradually "wither" (Shipa et al., 2021). Sometimes, people think they have controlled the main pests, but as a result, invasive species such as mealybugs (*Phenacoccus solenopsis*) take the opportunity to spread and become a new disaster (Razaq et al., 2019).

2.2 Impact of pests on yield and quality

The reduction in cotton production is often not caused by natural disasters but by pests. It has been estimated that if no control measures are taken at all, the yield loss caused by pests and diseases could be close to 60% (Malinga and Laing, 2024). This is not merely a matter of numbers; the damage caused by pests to cotton is often "both inside and out". Sucking pests cause plant growth to stagnate, leaves to turn yellow and fall off prematurely, cotton fibers to be short and coarse, and have poor toughness (Asif et al., 2024). Cotton bollworms are more direct, specifically targeting flower buds and cotton bolls. The cotton fluff is not long and full, and the quality naturally declines. The damage caused by scale insects and whiteflies is even more concealed. They spread viruses among cotton plants, dragging down the growth momentum of the entire cotton field. Although some regions can recover some losses through timely prevention and control, on the whole, pests remain the biggest "obstacle" affecting the yield and quality of cotton.

2.3 Challenges with chemical control methods

Pesticides were once regarded as the most effective means of pest control. For decades, cotton field management has been almost inseparable from it. But the problem is becoming more and more obvious. Many pests, especially cotton bollworms and piercing-sucking pests, have long developed resistance to commonly used pesticides, and their effectiveness is getting worse and worse. As a result, the dosage has to be increased over and over again. Broad-spectrum pesticides are even worse.

They have killed all their natural enemies, and as a result, secondary pests that were originally not threatening have become rampant. The consequences of long-term and frequent pesticide application go far beyond the issue of yield: the environment is polluted, farmers' health is threatened, and even soil and water bodies are damaged by pesticide residues (Nadeem et al., 2022). Meanwhile, the increase in pesticide prices has led to a continuous rise in the cost of cotton cultivation. Facing these realities, people have to rethink the control methods and combine biological control, crop resistance and ecological strategies (such as associated planting) to form a more robust and sustainable integrated pest management system (Figure 1) (Chi et al., 2021).

Figure 1 Typical modes of cotton intercropping. A, cotton-wheat mode. B, cotton-wheat-watermelon mode. C, cotton-potato mode. D, cotton-peanut mode. E, cotton-chili mode. F, cotton-mungbean mode. G, cotton-jujube mode. H, cotton sorghum mode (Adopted from Chi et al., 2021)

3 Biological Control as a Sustainable Strategy

3.1 Types of biological control agents used in cotton

In the cotton fields, there are actually quite a few "biological weapons" that can be put to good use. The earliest and most widely used were fungi, such as *Beauveria bassiana* and Metarhizium rileyi, which could infect lepidoptera larvae and sucking pests, causing the pests to "fall ill" themselves (Malinga and Laing, 2021). Bacterial preparations are also common. For instance, Bacillus velezensis (Bt) has almost become synonymous with insect control. There are also some rhizogenic bacteria (PGPR), such as Bacillus Velezensis, which have both pest control and nematode inhibition functions. In addition, viruses (such as nuclear polyhedral virus) and microsporidia can also exert pathogenic effects against specific pests, such as cotton bollworms (Malinga and Laing, 2022). Of course, don't forget the natural enemies. Ladybugs, lacewings, predatory stink bugs and various parasitic wasps (such as Trichogramma and wasp) are all quietly "helping" in the cotton fields, playing a natural control role in the pest population.

3.2 Mechanisms of pest suppression

These biological control measures do not function through a single mechanism. Fungi and bacteria infect the surface or interior of pests in a relatively direct way, inactivating the pests through toxin or tissue infection (Dannon et al., 2020). The role of predators and parasitic wasps is more like that of "natural police". They prey on or parasitize pests, gradually reducing the population size. Some rhizosphere bacteria take a different path: they do not directly kill insects but induce the cotton's own defense response, making the plant more resistant. There is another indirect way, by adjusting the field habitat, such as associated planting or intercropping, to attract more natural enemies to participate and form an ecological protective barrier (Cui et al., 2023).

3.3 Advantages of biological control

The benefits of biological control are often not limited to one aspect. The most obvious is that less chemical pesticides can be used, which not only reduces the environmental burden but also slows down the rate at which pests develop resistance (Bordini et al., 2021). Its "selectivity" is also a major advantage. Unlike broad-spectrum pesticides that are "one-size-fits-all", moderate use can preserve the population of natural enemies and maintain ecological balance (Xue et al., 2022). In terms of safety, biological control agents are milder to humans, animals and non-target organisms. Most importantly, it can be combined with other management methods to become the most stable part of the Integrated Pest Management (IPM) system, providing a more sustainable path for cotton cultivation.

4 Companion Planting for Pest Management

4.1 Functional roles of companion plants

In cotton fields, companion plants are often regarded as a kind of "natural assistant". Some plants can "lure away" pests, playing a role in attracting them. When pests are drawn to these attracting crops, farmers can deal with them in more concentrated areas (Annells et al., 2003). There are also some plants that are just the opposite. The odors they release can mask the odor signal of cotton, causing pests such as aphids to get lost and fail to find their targets (Blassioli-Moraes et al., 2022). In addition, companion plants also provide food and hiding places for beneficial insects, such as pollen, nectar or shady leaf clusters, thereby attracting and maintaining the number of natural enemies. There is another situation where cover crops like black velvet beans have little attraction to major pests. Pests tend to avoid these areas, and thus cotton becomes "safe" instead.

4.2 Enhancement of field biodiversity

Cotton has been planted for several consecutive years, and the fields are often "unusually quiet". With more pests and fewer natural enemies, the ecosystem becomes monotonous. However, once companion plants are introduced, this situation begins to loosen. When different crops are mixed together, the structure of the field becomes more complex. Natural enemies have places to hide and forage, and the number of predators and parasitic wasps also increases accordingly (De Araujo et al., 2024). The familiar habitats of pests have been disrupted, and their reproductive rhythms have also been disturbed. It is not so easy for them to break out (Yousefi et al., 2024).

Meanwhile, the activity of the soil has increased, and the resilience of the ecosystem is also recovering. Ultimately, diversification has brought the cotton fields back to life. Not only have there been fewer pests, but the system itself has also become more stable and better at adapting to changes.

4.3 Interactions with other pest control strategies

Companion cultivation itself is not a "panacea". It is very difficult to completely solve the pest problem in cotton fields by relying on it alone. The real effect often emerges when it is combined with other prevention and control measures. For instance, in an integrated pest management (IPM) system, companion plants are often used in conjunction with biological control agents and selective pesticides, forming a complementary relationship. Some companion plants can attract natural enemies, making biological control more effective. Some have reduced the dependence of pests on a single population through diversified planting structures (Quan and Wu, 2023; Razzaq et al., 2023). In genetically modified cotton systems, farmers sometimes interplant non-genetically modified crops as "refuge zones", which can slow down the emergence of pest resistance. There are exceptions. In some areas where the climate or the types of pests are special, the control effect of co-planting is not obvious. Overall, it is more like a part of a complete management plan and needs to be coordinated with other strategies to maintain ecological balance and stable yields while controlling pests.

5 Case Study: Field Applications of Biocontrol and Companion Planting

5.1 India: community-based biological control programs

In India, pest control is no longer as simple as spraying pesticides. In many places, the power of "people" has begun to be relied on. Integrated Pest management (IPM) projects involving farmers, communities and technicians have become a new way to control cotton bollworms and whiteflies. Some areas in the north are typical examples. Farmers do not merely rely on pesticides but have learned to monitor the number of pests, select cotton varieties with stronger resistance, decide whether to intervene based on economic thresholds, and combine it with the precise application of biopesticides (Kumar et al., 2020). The result was unexpected: the amount of pesticide used decreased significantly, but the output increased instead. Each hectare can save two to three thousand rupees. Even in the year when whiteflies broke out, the output of cotton down set a record. Similar experiences have also been replicated in Karnataka, where pheromone traps have been employed. Coupled with farmer training and timely intervention, the control effect has become more stable. With less input and less environmental burden, farmers' confidence has also significantly increased (Shreevani et al., 2024).

5.2 Africa: intercropping cotton with cowpea and maize

In Africa, farmers tend to deal with pests in a simple way by intercropping. Cotton, cowpeas and corn are planted in the same field. It seems messy, but in fact, there is a pattern. Researchers found in Zambia and Cameroon that such combinations could significantly reduce the number of pests, especially cotton bollworms and aphids. The number of aphids even decreased by more than 40% (Farsia Djidjonri et al., 2021; Silberg et al., 2024). Meanwhile, the number of natural enemies such as predatory beetles is increasing, the cotton bolls are developing more fully and the yield is more stable. Some statistics have shown that intercropping can increase the yield by an average of about 23%, and farmers' income also grows accordingly. Of course, this is not the same everywhere. The effects vary greatly due to differences in climate, soil conditions and management levels. It is worth mentioning that in some areas, intercropping of corn and cowpeas is no longer merely a pest control measure; it is regarded as a long-term strategy that balances yield and ecology.

5.3 Australia: combining *Beauveria bassiana* with pigeon pea rows

There are actually not many local studies on this aspect in Australia, but from the experiences of other regions, some practices worth learning from can still be found. Some people attempted to combine *Beauveria bassiana* with associated crops, and the results were quite satisfactory (Figure 2) (Mantzoukas et al., 2023). This fungus itself is a "natural enemy" of pests, capable of infecting insects such as lepidoptera larvae and rendering them inactive within a short period of time. If cardamom is planted simultaneously in cotton fields, the activity space of natural enemies will increase, and the number of pests will also decrease accordingly (Papantzikos et al., 2024). Although it seems to be just a simple combination, it has brought about a chain reaction, reducing the reliance on chemical pesticides, easing environmental pressure, and bringing cotton production closer to an organic and ecological direction. It can be said that this approach has not only made the cotton fields cleaner but also more "lively".

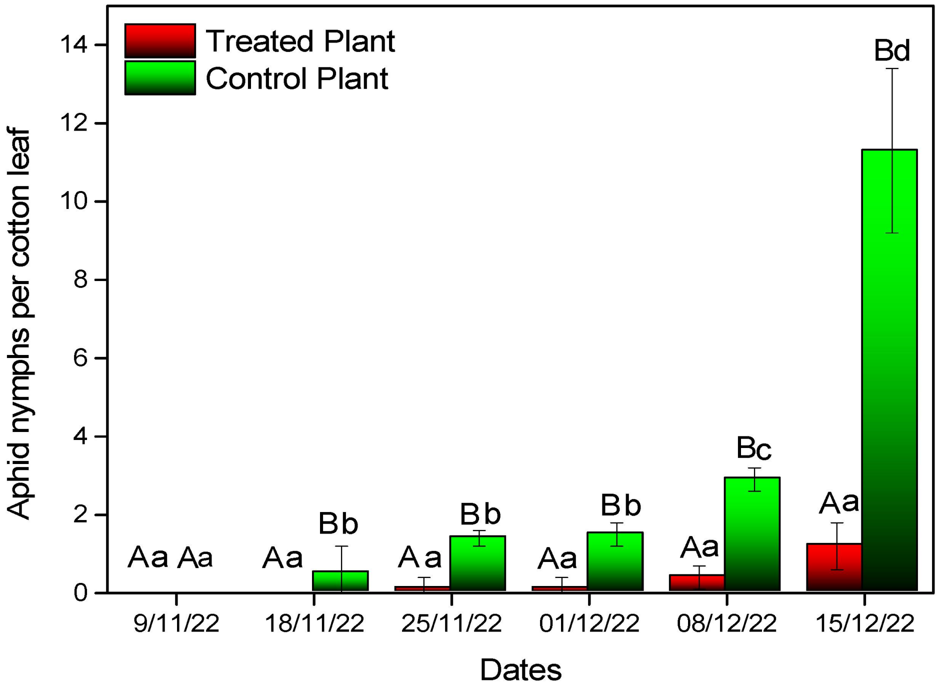

Figure 2 *A. gossypii* aphid population on the leaves of cotton plants after treatment with *B. bassiana*. Mean values of the same treatment with the same small letter are not significantly different; mean values of the same dates with the same capital letter are not significantly different (Tukey test: $p < 0.05$) (Adapted from Mantzoukas et al., 2023)

6 Integrated Pest Management (IPM) Approaches in Cotton

6.1 Principles of IPM in sustainable cotton production

In cotton cultivation, to achieve "high yield with less pesticide", relying on just one method is not enough. Integrated Pest Management (IPM) is more like a systems thinking approach that combines biological control, farming management, genetic resistance and chemical control, but pesticides are always the last resort. Typically, growers monitor the numbers of pests and their natural enemies by conducting regular field inspections and only take action when pests reach an economic threshold (Mensah and Singleton, 2003). At the same time, protecting natural enemies is an important part. Reducing interference with them is considered more cost-effective than simply "killing insects". At the tillage level, crop rotation, reasonable sowing time and the use of insect-resistant varieties can also effectively reduce the pressure of pests. When pesticides have to be used, selective products are preferred. They have a small impact on non-target organisms and can also delay the emergence of drug resistance (Zhou et al., 2024). These seemingly trivial links, when accumulated, form a relatively stable prevention and control system.

6.2 Synergistic integration of biocontrol and companion planting

The effectiveness of IPM often depends on whether the "combination punch" is played properly. Relying solely on biological control or companion cultivation each has its limitations, but when the two are combined, their effects will be significantly magnified. Associated plants can attract natural enemies, provide shelter and food, while microbial pesticides or parasitic natural enemies directly weaken pest populations (Kumari et al., 2024). In some areas, this combination not only suppresses pests but also delays the development of drug resistance. The combination of refuge zone cultivation of genetically modified cotton, biological control and ecological regulation has also slowed down the adaptation speed of pests (Lu and Li, 2024). Meanwhile, the diverse crop structure and ecological intervention make the system itself more "resilient", and even during peak pest periods, it is less likely to get completely out of control.

6.3 Outcomes of IPM adoption

Integrated Pest Management (IPM) sounds like a theoretical term, but when applied to fields, its effects are actually quite practical. The most obvious change is that less pesticides are used. The application rate of insecticides per hectare has significantly decreased, not only saving money but also causing less suffering to the soil and water (Manjunath, 2022). Interestingly, despite the reduction in input, the output has not declined. In many places, cotton has become more stable and high-yielding, and farmers' income has also risen accordingly. Ecologically, the differences can also be seen: the number of natural enemies has started to rise, pests no longer break out in a one-sided manner, and the balance of cotton fields is gradually being restored. What's even more surprising is that people are also changing. Through projects such as the farmers' Field School, cotton growers have developed their own judgments on pest identification and the timing of pest control, and no longer rely entirely on external instructions. It can be said that IPM brings not only new methods for pest control, but also a transformation that makes agriculture more autonomous and sustainable.

7 Environmental and Socioeconomic Impacts

7.1 Ecological benefits of reduced pesticide use

With less pesticide used, the ecological environment of the cotton fields will immediately be different. The number of natural enemies began to recover. "Industrious little workers" like ladybugs and predatory beetles increased again, while pests decreased (Ouyang et al., 2020). With less use of chemical agents, pollution in the air and water has decreased accordingly, and the risks to non-target organisms, especially beneficial insects and wild animals, have been greatly reduced. Intercropping, protective biological control and other practices have enabled the self-regulating ability of the ecosystem to come into play again, significantly reducing the frequency of pest outbreaks. The vicious cycle of "more pesticides being sprayed and more pests being treated" in the past has also been alleviated by reducing the use of broad-spectrum pesticides. More importantly, such ecological transformation is often long-term, and the resilience of the ecosystem is also enhanced accordingly.

7.2 Economic returns for smallholder and large-scale farmers

The use of pesticides has been reduced and money has been saved. For small-scale farmers, this change is the most direct. In countries like China, India, South Africa and Argentina, the promotion of genetically modified insect-resistant cotton combined with biological control has led to an increase in the output and profits of many farmers. Less spraying of pesticides means less purchase of pesticides and less labor, and the cost will naturally decrease. This is a practical relief for small-scale growers who are short of funds and have limited labor. On the other hand, intercropping and ecological control methods make it easier to control pests and diseases, reduce yield fluctuations, and make profits more stable. For large-scale farms, this system not only reduces input but also optimizes the production structure, making it more sustainable.

7.3 Social and policy dimensions

Less pesticide is used, and it is not only the cotton in the fields that benefits. The most direct change is actually people. The number of poisoning incidents among farm workers has decreased, and the health risks in rural communities have also declined accordingly. This kind of improvement is often overlooked because it is not as immediately visible as output. Meanwhile, the promotion of technology has become a crucial link. Without training and guidance, even the best biological control methods are hard to be truly implemented. The seemingly trivial links such as farmers' field schools, technicians going to the countryside, and experience sharing sessions actually determine whether ecological control can be sustained in the long term (Baker et al., 2020).

Of course, the role of policies should not be ignored either. Subsidies, rewards, regulatory support, and even market-oriented incentives can all promote the wider acceptance of biological control and intercropping (Jacquet et al., 2022). However, very often, it is the internal forces within the community that truly play a decisive role. Community-based integrated pest management is not merely a pest control method; it provides a reason for communication among farmers and builds trust. Everyone learns from and helps each other. Ecological prevention and control is no longer just a "technique", but has become a more cohesive production method.

8 Concluding Remarks and Future Prospects

The terms "biological control" and "intercropping" may not sound new, but their significance seems to have only been truly re-recognized in recent years. In the past, people relied more on pesticides and sprayed them whenever they saw insects. However, nowadays, more and more field experiments and studies tell us that these "ecological methods" can actually work. With fewer pests and more natural enemies, the quality and yield of cotton have not declined; instead, they have become more stable. Some farmers were initially skeptical, but after seeing the results in their fields, they gradually began to change their practices.

The emergence of the comprehensive prevention and control system has transformed these scattered experiences into a systematic one. When biological control agents, selective pesticides and ecological management are combined, the effect is often no worse than that of chemical control, and may even be better. More importantly, the burden on the environment has been alleviated and farmers' input has also decreased. The update of biological control agents and the promotion of the IPM concept have made the prevention and control of cotton pests no longer just a matter of "preventing pests once", but is transforming towards a more long-term and stable agricultural model.

However, there are still many problems. For instance, genetically modified insect-resistant cotton and biological control have indeed reduced the amount of pesticides sprayed, but new pest populations, especially piercing-sucking pests, are becoming new troubles. Drug resistance monitoring and classified management are becoming increasingly necessary. Furthermore, many biological control products perform well in laboratories, but they fail to adapt to the environment in the fields, with poor stability, high costs and unstable supply. This is particularly prominent in developing countries. There is another repeatedly mentioned shortcoming: knowledge. Research on the biological control effects at the landscape scale, how intercropping systems can be optimized, and the integrated application of new technologies (such as nanocarriers and precise pesticide application) remains limited. For small-scale farmers, the problems are more realistic: insufficient labor force, difficulty in obtaining technology, and limited resources of biopesticides and associated plants may all become stumbling blocks to promotion.

The path ahead probably needs to be more down-to-earth and systematic. Just having ideas is not enough. Details such as the stability of biological control agents, formula improvement, and application methods must all keep up. What works in the laboratory often "changes its nature" in the field. In addition, the framework for integrated pest management also needs to be further refined. Biological control, companion planting, insect-resistant varieties and precision agriculture should be combined to form a model that farmers can understand and follow.

But apart from technology, there are also policy issues. Subsidies, training, and research and development support must all keep up; otherwise, no matter how good the methods are, they will be in vain if farmers can't afford them. Promotion should not merely be confined to documents; someone needs to go down to the fields to enable farmers to participate in experiments and offer suggestions, rather than passively accepting "expert solutions". Pests change rapidly, and ecosystems are also evolving. Therefore, monitoring and adjustment have become the norm. Drug resistance, new pests and environmental feedback all need to be kept on the lookout at all times. There is no one-size-fits-all solution for agriculture. Only by learning and adjusting while working can cotton production truly move towards green, stable and sustainable development.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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