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Economic Evaluation of Biopesticides vs. Chemical Insecticides: Impact on Cotton Farming in South Africa

Lawrence Malinga[1-3]*, Mark Laing[3]

[1]South African Sugarcane Research Institute, Private Bag X02, Mount Edgecombe, 4300, South Africa.
[2]Agricultural Research Council –Industrial Crops, Private Bag X82075, Rustenburg, 0300, South Africa.
[3]School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Private Bag X01, Scottsville, Pietermaritzburg, 3209, South Africa.

***E-mail** ✉ lawrence.malinga@sugar.org.za

ABSTRACT

Cotton plays an important role in Africa's agricultural economy, yet its profitability is often challenged by high production costs. This study evaluates the cost-effectiveness of chemical insecticides—Chlorpyrifos® 480 EC, Karate® EC, and Bandit® 350 SC—against biopesticides—Eco-Bb®, Bolldex®, Delfin®, Nomu-Protec®, and Bb endophyte—in managing cotton pests. Among the tested pesticides, Delfin® incurred the highest expense at US$602, followed by Bolldex® at US$495.74, while Chlorpyrifos® was the most economical at US$28. Additional production costs amounted to US$1,396.50 per hectare, with labor being the most significant at US$544. The lowest production expenditure in the bollworm was observed with Karate® (US$1,455), whereas Delfin® had the highest (US$1,999). Bolldex® achieved the highest cotton yield (6,402 kg ha^{-1}), but Karate® had the greatest net profit (US$1,445.26 per hectare) and the best cost-benefit ratio (1.8). In the leafhopper, Bandit® produced the highest average seed cotton yield (6,394 kg ha^{-1}), followed by Bb endophyte (6,297 kg ha^{-1}). Net profit was highest with Bandit® (US$1,712), followed by Karate® (US$1,253), with Bandit® yielding the highest cost-benefit ratio (2). While biopesticides generally required higher investment than chemical insecticides, all treatments were financially viable.

Keywords: Cost analysis, Cotton, South Africa, Biopesticides, Bollworm, Leafhopper

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Introduction

Cotton a member of the Malvaceae family, is a major fiber crop cultivated worldwide [1]. Africa contributes approximately 8% to the global cotton market [2], with production primarily dominated by the farmers [3]. The cotton sector provides livelihoods for more than 350 million people, the majority of whom are small-scale growers in developing nations [4]. In Africa, cotton cultivation is typically carried out on small plots [5] and relies on family-run farms that require intensive labor [6]. Over 20 countries in Sub-Saharan Africa engage in cotton production [2], with more than 2,000 farmers and 250 commercial growing the crop across South Africa’s Northern Cape, Mpumalanga, Limpopo, KwaZulu-Natal, and North West provinces [7]. In 2019, the total cultivated area expanded by 42% for rain-fed cotton and 22% for irrigated cotton compared to the last season [7]. However, fiber quality and cotton yields remain vulnerable to various insect pests, significantly impacting production [8].

Chemical insecticides are widely used for pest management due to their availability and effectiveness [9]. Despite their advantages, excessive reliance on these pesticides has raised concerns regarding environmental pollution [10], water contamination, and human health risks [11]. Additionally, improper application can lead to resistance among target pests while harming non-target species [12]. By 2019, South Africa had registered more than 500 pesticide products [13].

Biopesticides offer an alternative approach that could help reduce chemical insecticide dependency, mitigate pest resistance, and enhance yields [14]. However, their adoption remains limited in developing regions, particularly among farmers [15]. In Sub-Saharan Africa, the integration of biopesticides faces challenges such as the lack of comprehensive Integrated Pest Management (IPM) programs [16], high costs, inconsistent field performance, and regulatory constraints [17]. Research into biopesticides in Africa dates back to the 1960s [18], but investment in their development and agricultural application has been insufficient [16]. In South Africa, biopesticide research and product availability have increased in past years, with over 30 registered products currently on the market [13]. Between 2014 and 2019, biopesticides accounted for around US$4 billion of the global insecticide market, which was valued at US$61.3 billion [19]. By 2022, industry forecasts estimated that the global biopesticide market had surpassed US$5.64 billion and was projected to grow to US$11.38 billion by 2028 [20].

Access to high-quality cotton seeds, fertilizers, and insecticides remains a challenge for small-scale farmers striving to enhance their production [21]. The rising costs of these essential inputs have significantly contributed to higher overall production expenses [2]. The adoption of Bt cotton has further added to financial burdens, as its technological fees make it more expensive than conventional varieties [22]. With the cost per hectare increasing over time, farmers have experienced a decline in profit margins, while fluctuations in cotton prices, input costs, and weather conditions continue to influence production levels [23]. Ensuring effective crop protection is vital for improving yields and profitability, as each production input is important in cotton farming. This study aims to assess the impact of these factors on overall production.

Additionally, understanding the financial feasibility of incorporating biopesticides into farming practices is essential for growers to make informed and profitable decisions. While the economic advantages of genetically modified cotton for farmers in South Africa have been extensively studied [24], there is a lack of research on the cost-benefit aspects of biological pest control in non-genetically modified cotton. Therefore, this study seeks to evaluate input costs and gross profit margins associated with cotton production, comparing the economic viability of chemical and biopesticide insecticides in non-genetically modified cotton farming.

Materials and Methods

Trial location, design, and planting

Field experiments aimed at managing leafhoppers and bollworms were carried out at the Agricultural Research Council in Rustenburg, South Africa (25°39.0 S, 27°14.4 E). The trials followed a random block design, while each treatment was replicated four times. DeltaOPAL, a conventional non-GM cotton variety developed by Monsanto, was sown under irrigated conditions.

Application of insecticides

For the bollworm trial, the effectiveness of Bb endophyte (University of KwaZulu-Natal, Bolldex®, Pietermaritzburg), Eco-Bb®, and Delfin® (Hilton, Andermatt Madumbi, KwaZulu-Natal) was assessed against the pyrethroid-based insecticide Karate® (Syngenta, Centurion) and an untreated control group. In the leafhopper trial, Bb endophyte, Eco-Bb®, and Nomu-Protec® (Midlands, Andermatt PHP) were tested alongside chemical insecticides Karate® EC, Bandit® 350 SC, and Chlorpyrifos® 480 EC (Arysta LifeScience, Durban), with an additional untreated control group.

Thirteen weeks after planting, insecticide applications began, continuing for ten consecutive weeks. Due to the UV sensitivity of biopesticides, spraying was conducted later in the day [25] using knapsack sprayers. Two laborers managed the insecticide application and weed hoeing, each earning a daily wage of US$10.87. The application process required 5 laborers per day over ten treatment days.

Cost-benefit assessment

The cost-benefit evaluation included expenses related to seeds, field preparation, pesticides, and trail maintenance. However, externalities such as environmental impacts, effects on beneficial insects, and potential risks to farmworkers and consumers were not factored into the analysis. Treatment and seed costs were obtained from suppliers, while the market price of seed cotton at the ginnery was used to determine the cost per kilogram.

The net return was calculated using a modified version of the formula from Ali *et al*. [26]:

$$\text{Net Return} = \text{Total revenue earned} - \text{Total cost of production} \quad (1)$$

Once input costs are subtracted, the net return represents the profit earned from selling seed cotton to a ginnery. Meanwhile, total revenue indicates the total amount received from the sale.

Cost-benefit ratio

The cost-benefit ratio was determined by analyzing the expenses associated with each treatment concerning the seed cotton yield. To calculate this ratio, the study applied the formula used by Gayi *et al*. [15] in previous cost-benefit analyses of similar treatments:

$$\text{Cost-Benefit Ratio} = \text{Total income earned} \div \text{Total cost of production} \quad (2)$$

The total income generated from selling seed cotton represents the overall revenue earned. Meanwhile, the total production cost accounts for all expenses involved in producing the cotton seed yield. To assess the benefit-cost ratio, the following index was applied: A seed cotton yield was considered economically viable if the benefit-cost ratio exceeded 1, whereas a ratio below 1 indicated an unsustainable yield. A break-even point was assumed at a benefit-cost ratio of exactly 1.

Results and Discussion

Pesticide costs

The cost of treatment per hectare is outlined in **Table 1**. The most expensive treatments were Bolldex® (US$495.74) and Delfin® (US$602.32). On the other hand, the lowest cost per hectare was recorded for Chlorpyrifos® 480 EC at just US$27.93. The cost of other treatments ranged between US$46.80 and US$226.44 per hectare.

Table 1. Cost comparison of biopesticides and chemical insecticides per hectare

Trade name	Active ingredient	Application rate	Unit price	Total cost*
Eco-Bb®	*Beauveria bassiana*	300 g/ha	US$22.64/300 g	US$226.44
Bolldex®	*Nucleopolyhedrovirus*	200 ml/ha	US$123.94/500 ml	US$495.74
Delfin®	*Bacillus thuringiensis*	1 kg/ha	US$60.23/kg	US$602.32
Bb endophyte	*Beauveria bassiana*	300 g/ha	US$22.64/300 g	US$226.44
NOMU-PROTEC®	*Metarhizium rileyi*	300 g/ha	US$22.64/300 g	US$226.44
Karate® EC	Lambda-cyhalothrin	120 ml/ha	US$49.06/l	US$58.87
Chlorpyrifos® 480 EC	Chlorpyrifos	200 ml/ha	US$13.96/l	US$27.93
Bandit® 350 SC	Imidacloprid	200 ml/ha	US$23.40/l	US$46.80

*Total cost is calculated based on ten applications per hectare at the recommended rate. The unit price was converted to USD using the 2018 exchange rate (ZAR 13.2488).

Production costs

Table 2 provides an overview of the input costs required to cultivate 1 hectare of cotton. Beyond the expense of pesticides, additional production costs added up to US$1,396.50 per hectare. These expenses covered seed purchases, land preparation, planting, weed control, pesticide application, and harvesting. Among these, the highest labor cost was incurred for manual weed removal (US$543.45), followed by harvesting costs (US$360.79).

The total production expenses for each treatment are displayed in **Tables 3–6**. In the bollworm trial, the lowest production cost was associated with Karate® EC (US$1,455.38 per hectare), while the highest cost was recorded for Delfin® (US$1,998.82 per hectare).

In the leafhopper trial, treatments using chemical insecticides proved to be the most economical. The least expensive treatments per hectare included Chlorpyrifos® 480 EC (US$1,424.43), Bandit® 350 SC (US$1,443.30), and Karate® EC (US$1,455.38). Conversely, treatments with Eco-Bb®, Bb endophyte, and NOMU-PROTEC® led to the highest production costs, reaching US$1,622.94 per hectare.

Table 2. Summary of input costs for additional production activities

Input	Quantity	Cost per hectare (US$)
Cottonseed	8 kg/ha	78.12
Ripping	Tractor rental per hectare	84.31
Discing	Tractor rental per hectare	56.23
Planting	Tractor rental per hectare	56.23
Manual hoeing	5 workers/day for 10 days @ US$10.87	543.45
Pesticide spraying	2 workers/day for 10 days @ US$10.87	217.38
Harvesting	Tractor rental per hectare	360.79
Total		**1,396.50**

Table 3. Cost-benefit analysis of chemical and biological insecticides in the 2017 cotton bollworm experiment

Treatment	Quantity	Cost per treatment (US$/ha)	Other costs (US$)	Total cost (US$)	Cotton yield (kg/ha)	Cost per kg (US$)	Income (US$/ha)	Net return (US$/ha)	Cost-benefit ratio
Control	0	0	1,396.50	1,396.50	4,168	0.45	1,887.57	491.06	1.4
Eco-Bb®	300 g	226.44	1,396.50	1,622.94	3,055	0.45	1,383.52	-239.42	0.9
Bolldex®	200 ml	495.74	1,396.50	1,892.25	5,987	0.45	2,711.34	819.09	1.4
Delfin®	1 kg	602.32	1,396.50	1,998.82	3,523	0.45	1,595.47	-403.36	0.8
Bb endophyte	300 g	226.44	1,396.50	1,622.94	3,100	0.45	1,403.90	-902.00	0.9
Karate® EC	120 ml	58.87	1,396.50	1,455.38	5,133	0.45	2,324.59	869.21	1.6

Costs are based on ten applications per season.

Table 4. Cost-benefit analysis of chemical and biological insecticides in the 2018 cotton bollworm experiment

Treatment	Quantity	Cost per treatment (US$/ha)	Other costs (US$)	Total cost (US$)	Yield (kg/ha)	Cost per kg (US$)	Income (US$/ha)	Net return (US$/ha)	Cost-benefit ratio
Control	0	0	1,396.50	1,396.50	4,673	0.45	2,116.27	719.76	1.5
Eco-Bb®	300 g	226.44	1,396.50	1,622.94	5,961	0.45	2,699.57	1,076.63	1.7
Bolldex®	200 ml	495.74	1,396.50	1,892.25	6,818	0.45	3,087.68	1,195.43	1.6
Delfin®	1 kg	602.32	1,396.50	1,998.82	5,755	0.45	2,606.27	607.45	1.3
Bb endophyte	300 g	226.44	1,396.50	1,622.94	6,409	0.45	2,902.45	1,279.51	1.8
Karate® EC	120 ml	58.87	1,396.50	1,455.38	6,405	0.45	2,900.64	1,445.26	2.0

Costs are based on ten applications per season.

Table 5. Cost-benefit analysis estimates for chemical and biological insecticides in the cotton leafhopper experiment (2017)

Treatment	Quantity	Treatment cost* (US\$ ha^{-1})	Other costs (US\$)	Total cost (US\$)	Yield (kg ha^{-1})	Cost per kg (US\$)	Income (US\$)	Net return (US\$ ha^{-1})	Cost-benefit ratio
Control	0	US\$0	US\$1,396.50	US\$1,396.50	4,810	US\$0.45	US\$2,178.31	US\$781.81	1.6
Eco-Bb®	300 g	US\$226.44	US\$1,396.50	US\$1,622.94	5,960	US\$0.45	US\$2,699.11	US\$1,076.17	1.7
Bb Endophyte	300 g	US\$226.44	US\$1,396.50	US\$1,622.94	5,830	US\$0.45	US\$2,640.24	US\$1,017.30	1.6
NOMU-PROTEC®	300 g	US\$226.44	US\$1,396.50	US\$1,622.94	5,600	US\$0.45	US\$2,536.08	US\$913.14	1.6
Karate® EC	120 ml	US\$58.87	US\$1,396.50	US\$1,455.38	5,980	US\$0.45	US\$2,708.17	US\$1,252.79	1.9
Chlorpyrifos® 480 EC	200 ml	US\$27.93	US\$1,396.50	US\$1,424.43	5,020	US\$0.45	US\$2,273.41	US\$848.98	1.6
Bandit® 350 SC	200 ml	US\$46.80	US\$1,396.50	US\$1,443.30	5,820	US\$0.45	US\$2,635.71	US\$1,192.41	1.8

Note: Treatment costs are based on ten applications per season.

Table 6. Cost-benefit analysis estimates for chemical and biological insecticides in the cotton leafhopper experiment (2018)

Treatment	Quantity	Treatment cost* (US\$ ha^{-1})	Other costs (US\$)	Total costs (US\$)	Cotton yield (kg ha^{-1})	Cost per kg (US\$)	Income (US\$)	Net return (US\$ ha^{-1})	Cost-benefit ratio
Control	0	US\$0	US\$1,396.50	US\$1,396.50	5,090	US\$0.45	US\$2,305.11	US\$908.61	1.7
Eco-Bb®	300 g	US\$226.44	US\$1,396.50	US\$1,622.94	6,320	US\$0.45	US\$2,862.15	US\$1,239.21	1.8
Bb Endophyte	300 g	US\$226.44	US\$1,396.50	US\$1,622.94	6,763	US\$0.45	US\$3,062.77	US\$1,439.83	1.9
NOMU-PROTEC®	300 g	US\$226.44	US\$1,396.50	US\$1,622.94	6,300	US\$0.45	US\$2,853.09	US\$1,230.15	1.8
Karate® EC	120 ml	US\$58.87	US\$1,396.50	US\$1,455.38	5,340	US\$0.45	US\$2,418.33	US\$962.96	1.7

Chlorpyrifos® 480 EC	200 ml	US$27.93	US$1,396.50	US$1,424.43	6,310	US$0.45	US$2,857.62	US$1,433.19	2.0
Bandit® 350 SC	200 ml	US$46.80	US$1,396.50	US$1,443.30	6,968	US$0.45	US$3,155.61	US$1,712.31	2.2

Note: Treatment costs are based on ten applications per season.

Bollworm experiment

The analysis of the pesticide treatments used in the cotton trials is provided in **Tables 3 and 4**. In 2017, the treatments of Delfin®, Eco-Bb®, and Bb endophyte resulted in lower seed cotton yields than the control. In contrast, Bolldex®-treated plots produced the highest yields, reaching 5,987 kg ha-1 in 2017 and 6,818 kilogram ha-1 in 2018, representing a 45% improvement over the control.

Leafhopper experiment

When compared to the untreated control, all pesticide treatments increased seed cotton and provided greater net returns than the cost of production, as shown in **Tables 5 and 6**. Karate® EC was the top performer in 2017 with 5,983 kg ha-1, followed by Eco-Bb® at 5,963 kg ha-1. Chlorpyrifos® 480 EC produced the lowest yield, with 5,021 kg ha-1. Bandit® 350 SC had the highest yield in 2018 at 6,968 kg ha-1, with Bb endophyte coming second at 6,763 kg ha-1. Karate® EC had the smallest yield, producing 5,340 kg ha-1.

Gross income

Bollworm experiment

The gross income data for each treatment are summarized in **Tables 3 and 4**. With an average price of US$0.45 per kilogram, Bolldex® generated the highest gross income of US$2,711.34 in 2017 and US$3,087.68 in 2018. The lowest gross income in 2017 came from Bb endophyte (US$1,403.90) and Eco-Bb® (US$1,383.52). In 2018, the untreated control earned the least, with US$2,116.27, followed by Delfin® at US$2,606.27. Gross income for the treatments ranged from US$2,606.27 to US$3,087.68.

Leafhopper experiment

The summary of gross income for the leafhopper experiment in both seasons is shown in **Tables 5 and 6**. Karate® EC (US$2,708.17) and Eco-Bb® (US$2,699.11) produced the highest gross income in 2017, while Chlorpyrifos® 480 EC had the lowest at US$2,273.41. Gross income for the treatments ranged from US$2,273.41 to US$2,708.17, while the control earned US$2,178.31. In 2018, Bandit® 350 SC generated the highest gross income of US$3,155.61, and Karate® EC earned the lowest at US$2,418.33. The other treatments yielded gross incomes between US$2,857.62 and US$3,062.77.

Net income

Bollworm experiment

Net income data for each treatment during 2017 and 2018 are provided in **Tables 3 and 4**. In 2017, Karate® EC generated the highest net income of US$869.21, while Delfin® showed the lowest net income at -US$403.36. Delfin®, Bb endophyte, and Eco-Bb® all had lower net incomes compared to the control. Other treatments showed net income results ranging from -US$239.42 to US$819.09. In 2018, Karate® EC continued to lead with the highest net income of US$1,445.26, while Delfin® remained the lowest at US$607.45. Other treatments had net incomes ranging from US$1,076.63 to US$1,279.51.

Leafhopper experiment

In both experimental seasons, all pesticide treatments outperformed the untreated control in terms of net income, as shown in **Tables 5 and 6**. In the 2017 season, Karate® EC yielded the highest net income of US$1,252.79, while Chlorpyrifos® 480 EC resulted in the lowest net income of US$848.98. The other treatments produced net incomes ranging from US$913.14 to US$1,192.41. In 2018, Bandit® 350 SC achieved the highest net income of US$1,712.31, following Bb endophyte at US$1,439.83. Karate® EC had the lowest net income that year, at US$962.96, with other treatments ranging from US$1,230.15 to US$1,433.19.

Cost-benefit ratio

Bollworm experiment

The cost-benefit ratios for the bollworm experiment are detailed in **Tables 3 and 4**. In 2017, Karate® EC recorded the highest ratio of 1.6, followed by Bolldex® and the control with 1.4. Eco-Bb® and Bb endophyte had ratios of 0.9, while Delfin® had the lowest ratio of 0.8. In 2018, Karate® EC led with a ratio of 2, followed by Bb endophyte at 1.8 and Eco-Bb® at 1.7. Across both years, Karate® EC consistently achieved the highest cost-benefit ratio.

Leafhopper experiment

For the leafhopper test, the cost-benefit ratios for the 2017 and 2018 seasons are presented in **Tables 5 and 6**. In 2017, Karate® EC had the highest cost-benefit ratio of 1.9, while the lowest ratio of 1.6 was observed for Bb endophyte, NOMU-PROTEC®, Chlorpyrifos® 480 EC, and the control. In 2018, the ratio for Karate® EC and management was 1.7, Eco-Bb® and NOMU-PROTEC® had ratios of 1.8, and Bb endophyte had a ratio of 1.9. Chlorpyrifos® 480 EC and Bandit® 350 SC had the highest cost-benefit ratios of 2 and 2.2, respectively.

Cotton production challenges in Sub-Saharan Africa

Cotton production in Sub-Saharan Africa faces competition from other crops due to declining productivity, often linked to external factors such as fluctuating market prices and rising production costs. Reducing input costs is as important as increasing productivity, given the competitive nature of the cotton market. The climate, cost-effective inputs, and the success of the cotton industry play a significant role in its productivity. Fluctuations in supply and demand, along with changes in the global cotton market, contribute to price volatility. The net income in this study varied depending on the treatment, reflecting differences in input costs and yields.

treatment costs

The results indicate that biopesticides were considerably more expensive than conventional pesticides. Delfin® was the most costly, at US$602.32 per hectare for 10 sprays. In contrast, chemical insecticides typically cost under US$100 per hectare, likely due to fixed costs and their widespread use in the farming community [26-29]. Ali *et al*. [26] noted that seed costs in Pakistan have remained stable despite increased pesticide use. Bolldex® (HaNPV) was also found to be an expensive treatment, costing US$495.74 per hectare. In a study by Ojha *et al*. [29], HaNPV was also identified as the most expensive treatment, followed by *B. bassiana* for *H. armigera*, while *B. thuringiensis* was considered a cheaper alternative. In Kenya, farmers spent an average of US$131 per hectare on *B. bassiana* and US$95 per hectare on *B. thuringiensis*. Olson [30] reported that biopesticide development costs up to US$10 million and four years, compared to the US$250 million and nine years required for chemical pesticide development and regulation. According to Constantine *et al*. [28], the affordability and availability of biopesticides, as well as their perceived effectiveness, are key factors limiting their use by small-scale farmers.

Costs of other inputs

To remain competitive in cotton markets, it is crucial to maximize yields while minimizing production costs, as highlighted by Amrouk *et al*. [31]. Cotton pest management incurs several additional costs, including those for cultivation, seed, harvesting, labor, and weed control. In Pakistan, input costs related to irrigation and land preparation contribute positively to revenue, whereas pesticide and fertilizer costs tend to reduce profits [32]. Expanding the cultivated area helps distribute production costs across more cotton acres, which enables farmers to share expenses between crops and enhance profit [33].

Labor costs

Labor remains the most significant expense in cotton production [34]. For small-scale cotton farmers with limited financial resources, labor wages often serve as their primary source of income [35]. Family labor is commonly employed, with output levels depending on the amount of cotton a family can do [36]. Blaise and Kranthi [37] found that labor costs constitute the largest share of production expenses, while Belay *et al*. [35] noted that a considerable portion of Ethiopia's input costs is attributed to equipment and labor. In Bangladesh, labor costs represent 28.6% of total cotton production expenses, while in India, this can rise to as much as 50 percent [38, 39]. In Turkey, labor and pesticide expenses are among the primary cost factors, with larger farms experiencing higher overall costs [40]. Even with China's substantial cotton support program, labor costs have continued to climb, further increasing production costs [41].

Weed control and harvesting costs

Weed control via hand hoeing proved to be the costliest method, with a total expense of $543.45. The effectiveness of weed control strategies in large cotton fields is complicated by varying soil and weed species conditions [42]. To combat weeds, farmers are told to implement a combination of crop rotation, hand harvesting, soil cultivation, and herbicide applications [43]. One strategy to reduce labor costs in weed control is using strip-tillage systems [44]. Mishra *et al*. [45] highlighted that manual harvesting is among the most expensive activities in cotton production due to its labor-intensive nature. They manage that mechanical harvesting can lower costs. Additionally, Bai *et al*. [46] emphasized the importance of mechanization and precise sowing techniques to reduce labor costs in cotton farming.

Yield

Cotton yield is a major determinant of both net profit and gross margin. Weather conditions and common issues such as pests, weeds, and diseases significantly influence cotton yields each year [47]. In the bollworm experiment, yields ranged from 4,500 to 6,400 kg per hectare, while in the leafhopper experiment, yields ranged from 5,600 to 6,900 kg per hectare. Plots treated with Delfin®, Bb endophyte, and Eco-Bb® produced the lowest yields of less than 3,600 kg per hectare in 2017. In comparison, the mean yield of irrigated cotton in South Africa that year was 4,411 kg per hectare [48]. According to the FAO [49], irrigated cotton yields typically range from 4,000 to 5,000 kg per hectare, with a lint percentage of 35%.

Income

The bollworm and leafhopper experiments produced the highest gross incomes of US$3,087.68 and US$3,155.61, respectively, based on a mean rate of US$0.45 per kilogram from the ginner. The lowest gross income in the bollworm experiment was US$1,383.52, while the leafhopper experiment produced the least revenue, US$2,273.41. The low yields in the bollworm experiment during 2017 were responsible for the reduced income. When harvested mechanically, irrigated cotton in South Africa yields around 5,000 kg per hectare and generates gross revenues exceeding US$3,000 per hectare at US$0.57 per kg [50]. The break-even point for mechanical harvesting is estimated to be US$285.31 per kg. Reddy [51] mentioned that, between 2010 and 2015, the average gross income per hectare in India was US$1,091.42, with an average net income of US$138.05. In South Africa, the average gross agricultural production value reached US$20.67 million in 2017, increasing by 29.3% to US$22.49 million in 2018 [52]. In that period, the price for seed cotton was US$0.60 per kg in 2017 and US$0.56 per kg in 2018. The prices are influenced by seasonal fluctuations and the grading of cotton lint, which impacts different ginners.

After accounting for production costs, Karate® EC-treated plots resulted in the highest net income among all treatments. Cole *et al*. [53] found that Karate® EC led to a 12% yield increase without significantly altering the predator-to-pest ratios. Similarly, Mink [54] showed that Karate® applications resulted in higher yields compared to untreated Bt cotton, and Javaid *et al*. [55] observed substantial yield improvements in Mozambique with Karate® pest control.

Cost-benefit ratio

To maximize profitability, farmers need to carefully choose the inputs used in cotton production, as this directly affects their cost-benefit ratio [56]. This ratio helps assess the economic effectiveness of different inputs [57], and as noted by Wei *et al*. [32], it also shows how much profit can be generated from a specific economic activity. A higher ratio means a better return on investment for farmers. The results from this study indicate that most treatments provided a positive return on investment, with treatments like Chlorpyrifos® 480 EC, Bandit® 350 SC, and Karate® EC having significantly higher cost-benefit ratios compared to the biopesticides. Biopesticides were found to be more costly, negatively impacting their cost-effectiveness. In the 2017 bollworm experiment, the low seed cotton yields led to net losses of up to US$403.36 per hectare for Delfin®, Eco-Bb®, and Bb endophyte treatments, resulting in cost-benefit ratios below 1. Karate® EC consistently showed the best cost-effectiveness among all treatments. Similar to our findings, Patel and Das noted that fields treated with lambda-cyhalothrin had a high cost-benefit ratio. This is why farmers in Uganda have turned to lambda-cyhalothrin for their cotton crops [15]. Lambda-cyhalothrin has also been found to provide favorable returns for crops like chickpeas [58], pigeon peas [59], and mung beans [60].

In contrast, Rudramuni *et al*. [61] observed lambda-cyhalothrin as one of the least cost-effective options against bollworms and sucking pests, which differs from our observations. Gadage *et al*. [62], in a 2009 study, reported that Beauveria bassiana had the best cost-benefit ratio (1:9.46), followed by Nomuraea rileyi (1:7.66) and HaNPV (1:3.97). However, in this study, the highest cost-benefit ratios were not achieved with the biopesticide treatments (Eco-Bb® and Bb endophyte). In the leafhopper experiment, Bandit® 350 SC and Chlorpyrifos® 480 EC showed the highest cost-benefit ratios, 2 and 1.8, respectively, due to their lower treatment costs. Balakrishnan *et al*. [63] found that chlorpyrifos 20 EC had a favorable cost-benefit ratio of 1:3.66 against H. armigera on cotton, while HaNPV had a ratio of 1:3.50. Even with its higher cost, Bolldex® achieved a respectable ratio of 1.5. Jeyarani *et al*. [64] also found a favorable cost-benefit ratio of 1:2.48 with HaNPV isolates, suggesting that biopesticides can be competitive when managed effectively.

Conclusion

The profitability, cost-effectiveness, and overall benefit of each treatment were largely influenced by its cost, input expenses, and yield. For cotton farmers, it is essential to enhance productivity while keeping costs as low as possible by selecting the right agricultural inputs and adhering to effective farming practices. While some treatments in this research resulted in higher yields, their high costs led to cost-benefit ratios, and lower net income as reflected in the cost-benefit analysis. Although biopesticides tend to be more expensive than chemical pesticides, their use largely depends on the severity of pest infestations. All the biopesticides tested in this study showed cost-benefit ratios greater than 1, making them viable options for inclusion in a pest management strategy. This research highlights key considerations for farmers when making decisions based on a more detailed analysis of costs and benefits.

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